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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL INFORMATION MEMORANDUM

REPORT NO: NAWCADPAX/TIM-2014/7

SWATCH TESTING AT ELEVATED WIND SPEEDS

by

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Dr. Jonathan Kaufman
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14. ABSTRACT

As part of a program to develop a systematic method to test and quantify Individual Protective Equipment (IPE) effectiveness, a methodology for the testing of IPE material at elevated wind speeds was developed. This effort involved the creation of two dissemination systems, devices to hold the swatch material, and instrumentation and sampling techniques needed for wind tunnel use. A fumed silicate, Aerosil 380, with an agglomeration size of approximately 100 nm and Dioctyl sebacate were used as the challenges. Wind tunnel tests were conducted for speeds of 3.0 m/sec, 6.1 m/sec, 9.1 m/sec, 13.2 m/sec, 18.3 m/sec, 27.4 m/sec, and 30.5 m/sec and the system and methodology developed were shown to give spatially and temporally repeatable results. Tests were conducted on was a 2/1 right-hand (denim), 100% cotton twill weighing 10 oz./yd^2 purchased from JoAnn Fabrics. The data show that increasing wind speed resulted in increasing penetration when an ambient velocity equivalent face velocity was maintained. The results were found to be consistent and repeatable and correlated well with data results taken at another facility using different instrumentation and procedures. A bench top swatch testing system was developed and correlated well with the wind tunnel swatch results at the equivalent face velocity. Aerosil, with a density 20 times less than Dioctyl sebacate, was found to have particle penetration from 10% to 30% less than the Dioctyl sebacate particle penetration. The ability to correlate bench top swatch testing and the new wind tunnel swatch technique allows the systematic testing IPE components, such as fasteners, seams, and closures, for improved system performance.

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SUMMARY

As part of a program to develop a systematic method to test and quantify Individual Protective Equipment (IPE) effectiveness, a methodology for the testing of IPE material at elevated wind speeds was developed. This effort involved the creation of two dissemination systems, devices to hold the swatch material, and instrumentation and sampling techniques needed for wind tunnel use. A fumed silicate, Aerosil 380, with an agglomeration size of approximately 100 nm and Dioctyl sebacate were used as the challenges. Wind tunnel tests were conducted for speeds of 3.0 m/sec, 6.1 m/sec, 9.1 m/sec, 13.2 m/sec, 18.3 m/sec, 27.4 m/sec, and 30.5 m/sec and the system and methodology developed were shown to give spatially and temporally repeatable results. Tests were conducted on was a 2/1 right-hand (denim), 100% cotton twill weighing 10 oz./yd^2 purchased from JoAnn Fabrics. The data show that increasing wind speed resulted in increasing penetration when an ambient velocity equivalent face velocity was maintained. The results were found to be consistent and repeatable and correlated well with data results taken at another facility using different instrumentation and procedures. A bench top swatch testing system was developed and correlated well with the wind tunnel swatch results at the equivalent face velocity. Aerosil, with a density 20 times less than Dioctyl sebacate, was found to have particle penetration from 10% to 30% less than the Dioctyl sebacate particle penetration. The ability to correlate bench top swatch testing and the new wind tunnel swatch technique allows the systematic testing IPE components, such as fasteners, seams, and closures, for improved system performance.

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NOMENCLATURE

A	Swatch area, 22.68 cm^2
N	Number of particles
P	Penetration
Q	Volumetric flow rate, cm^3
U_o	Face velocity, 6.5 cm/sec
V_∞	Wind Tunnel Velocity, m/sec

INTRODUCTION

Complete isolation from a chemically or biologically contaminated environment provides the best protection against percutaneous effects. This has been the goal of many individual protective equipment (IPE) designs; current ensembles intended to protect users against exposure to high CB concentrations (e.g., U.S. Marine Corps Chemical Biological Incident Response Force Level A chemical protective overgarment) achieve this isolation by sealing users in a chemically impermeable garment. Heat stress becomes a major problem with this approach; however, as normal physiological heat loss mechanisms (especially sweat evaporation) are blocked. Air-permeable materials with treated activated carbon were introduced to mitigate the heat stress problem without compromising CB protection.

The flowrate through air-permeable materials results from pressure differentials between the inside and outside of the garment. These pressure differentials are induced by body motions, e.g., the well known “bellows effect”, as well as by wind. The wind can be the actual outdoor wind, an artificial wind created by helicopter downwash, or a relative wind created by riding on a moving vehicle.

Previous evidence, reference 1, suggested that maintaining IPE protection levels becomes a problem with elevated wind speeds (e.g., some swatch tests show up to 300X increases in IPE penetration with a 3X increase in wind speed). Generally, swatch, component, and system test results along with modeling trend in the same direction (elevated wind speed increases penetration) but did not uniformly indicate the problem is of the same order of magnitude.

Moreover, these results were controversial because much of the data is derived from test methodology that is largely un-validated for assessing the effects of elevated wind speeds. For example, data obtained from the Aerosol/Vapor/Liquid Assessment Group swatch test exceed the design parameters of the test cell (i.e., design nominal equivalent wind speed of 3.6 m/sec).

A limited understanding of system-level (full garment) high wind issues based on a lack of high wind speed penetration and deposition studies, combined with combined un-validated test technology to study this issue, has become increasingly relevant as IPE requirements begin to address high wind-associated penetration. The present project was designed to investigate swatch and component tests in the presence of high winds (up to 36.6 m/sec (120 ft/sec or 81.8 mph)). This paper describes the development of test methodology and results for swatch testing of fabric material in the wind tunnel.

EXPERIMENTAL APPARATUS

WIND TUNNEL

The tests were conducted in the Naval Aerodynamic Test Facility (NATF) wind tunnel located at Patuxent River, MD, reference 2 describes the NATF. The NATF is a 1.22 m by 1.22 m by 2.44 m long (4 ft by 4 ft by 8 ft long) closed test section, open-return wind tunnel, see Figures A-1 and A-2. The facility incorporates a 200 hp motor that drives a variable pitch, variable RPM fan and delivers a maximum velocity of 60.96 m/sec (205 ft/sec or 140 mph). In addition, the facility has honeycomb and three sets of flow conditioning screens that minimize free stream turbulence intensity to approximately 0.5% and free stream velocity differences to 1%.

AEROSOL CHALLENGE

In this study, two aerosol challenges were used: Aerosil 380 manufactured by Degussa (Frankfurt am Main, Germany) and Dioctyl sebacate (DOS) manufactured by Sigma-Aldrich (St. Louis, MO). Aerosil 380 is a hydrophilic fumed silicate with a specific surface area of 380 m^2/g. The average primary particle size is 7 nm, though the agglomerated size is much greater. Originally, the material was tagged with fluorescein in order to be used for deposition studies. Results showed little difference in penetration between tagged and untagged Aerosil: this report utilizes untagged Aerosil in the results. DOS is a plasticizer that is liquid at room temperature and has a density of 0.914 g/mL. Aerosil challenge bulk density was measured using the ASTM D1895B method and included two controls: Arizona road dust and glass spheres.

DISSEMINATION SYSTEM

Common wind tunnel aerosol dissemination utilizes an array of tubing with ejectors (usually in the tunnel contraction or settling chamber) that allow dissemination across the wind tunnel cross section. This method proved to be unattractive for use in the NATF. The open-return design of the tunnel, while allowing constant temperature operation through heat exchange with the building HVAC system, requires continuous dissemination. However, due to the large amount of air volume moved through the wind tunnel, 4785.5 m^3/min (169,000 CFM) at the highest envisioned testing velocity of 53.6 m/sec, it was impractical to disseminate seeding in the complete test section. The facility HVAC system is not a separate system from the rest of the large office building and complaints regarding the adverse effects of the seeding particles are a concern (as are concerns regarding adverse effects on wind tunnel personnel). Also, an array of ejectors downstream of the flow conditioning screens would adversely affect wind tunnel flow quality. Low and high free-stream turbulence levels are of interest to insure that the test methodology is robust enough for use in other facilities: low turbulence flow would be compromised by ejectors in the wind tunnel contraction section. Finally, the facility is principally an aerodynamic research facility with delicate and expensive instrumentation: the seeding must not harm other equipment. These design considerations led to adopting localized seeding of the wind tunnel cross section. The localized seeding method has the added potential benefit of being portable from one facility to another. This mitigates one design variable in conducting the experiments in different facilities.

The original idea for dry particle dissemination was based on previous Particle Image Velocimetry tests in the NATF that required uniform dissemination of seed particles across a localized area of the wind tunnel cross section. A dispersion box, 28 in. by 18 in. by 21 in., was manufactured that uniformly injected particles into the tunnel ahead of the contraction section. The particles passed through the tunnel flow treatment (honeycomb and three screens) and contracted into a smaller area (approximately 8 in. by 10 in.) that could be positioned at the material specimen location, see Figure A-3. The dispersion box was modified by an electrical-grade aluminum lining and grounded to the wind tunnel. The air-cap spray head ejected Aerosil into a capped pipe that radially ejected the particles into the box. Downstream of the dispersing head was an internal 51% porous baffle plate, see inset Figure A-3. To assist with mitigation of momentum losses caused by the blockage of the box ahead of the tunnel contraction section, a commercial vacuum cleaner, operating in the blower mode, blew into the dispersion box.

Following the design of the dispersing box, a manner of dispensing the aerosol was needed. Aerosil particles are sufficiently small that they flow like a liquid lending themselves to dispersion by a paint sprayer or similar device. Polystyrene latex spheres or an atomized liquid also might be used in such a system. As a prototype, a paint spray nozzle (W.R. Brown Co., North Chicago, Illinois, Model Speedy) and associated pressure tank (2.5 gal) were modified; the siphon tube of the tank was replaced with a Laskin nozzle to loft Aerosil particles. While showing promise, it was realized this design was far from optimal. Aerosil is prone to acquiring static charge and this necessitated the replacement of all non-conducting lines and parts with conducting material. Additionally, all components of the spray system were grounded to the earth-grounded wind tunnel. The installed system is shown mounted ahead of the wind tunnel in Figure A-4. This method improved dispersion performance after these modifications were made.

The system was then modified to incorporate an atomizing nozzle (Spray Systems, Co., Wheaton, Illinois, 1/4JAUMCO-316SS2050) and the original pressure tank was replaced with a 5 gal pressure tank equipped with an air agitator (DeVilbiss, Glendale Heights, Illinois, QMST-5523). The pressure of the tank was generally set to 25 psi and the pressure of the lines to the dissemination system, after losses due to lines and the dryer, was 8 psi for Aerosil dissemination. The air agitator was needed to improve uniformity of the aerosol spray. Over time, the aerosol was found to settle away from the Laskin nozzle to the point that the nozzle was no longer effective in lofting the particles to the outlet line.

To insure that Aerosil was not contaminated, clean, dry Nitrogen was sent to the atomizer "air" line. Further, the atomizing-nozzle, needle valve and nitrogen were controlled by solenoid valves with ¼ in. lines (Skinner Valve, New Britain, CT, 7131T).

Initial tests of the system showed that the particles could be disseminated but not uniformly enough to provide repeatable results. The Aerosil was then mixed in a 200 proof ethanol solution that proved more repeatable but had the disadvantage of generating a large ethanol peak in particle size measurements that was difficult to mitigate.

An alternative dissemination system designed at Clarkson University was modified and incorporated for the NATF. This system used the air atomizing head (Spray Systems, Co.) used previously but was now placed in a pressure vessel. The atomized spray was sent through a dryer to a dissemination array placed in the wind tunnel test section (Figures A-5 through A-8). The dryer consists of a capped, clear, 10.2 cm (4 in.) OD PVC pipe, within which a porous metal tube (Mott Corp., Farmington, Connecticut, 1.9 cm (¾ in. ID) was immersed in a bed of silica beads. The dryer eliminated most of the ethanol evidenced by a pre-drying peak centered at 50 nm. Post-dryer, only the peak centered at 100 nm and associated with the aerosol challenge remained. As will be shown in subsequent sections, this arrangement was found to give temporally and spatially repeatable dissemination.

Untagged and tagged Aerosil as well as tagged Cabosil were successfully disseminated. In general, particles, 0.1% by mass, were mixed in 200 proof Ethanol. The final particle concentration was determined after trial and error. The initial concentration tried was 1% by weight. At such a high concentration the spray head was found to clog and temporal repeatability suffered. Early experimentation had reduced the concentration to 0.1% until clogging issues were minimized while still allowing an adequate particle count. Nevertheless, a regime of spray head cleaning had to be implemented to minimize test disruption. Frequent agitation using the fluid pressure tank agitator shown in Figure A-5 helped to insure consistency of the dissemination.

The DOS was disseminated using the same system but with some slight modifications, see Figures A-6 and A-7. A series of vents were placed between the dryer stage and the dissemination head to reduce the particle concentration to acceptable levels. Originally, the vents were filtered using Pall Corporation Model 12144 filters but as these became clogged over the course of testing without a ready replacement supply on hand, the filters were removed. In addition, the dissemination tank pressure was reduced to 6 psi to reduce the amount of particle generation.

The challenge was ejected in the wind tunnel via a series of ¼ in. tubing arranged in a square pattern and oriented facing forward to assist in mixing, see Figure A-8.

For bench top swatch testing, 0.1% Aerosil was mixed with distilled water. The water was removed from the particles using a desiccant dryer and a BGI, Inc. (Walthan, MA) 6-jet Collison Nebulizer was used to create the atomized particles.

SWATCH MATERIAL

Unless otherwise noted, the material used in the present report was a 2/1 right-hand (denim), 100% cotton twill weighing 10 oz/yd^2 purchased from JoAnn Fabrics on 21 May 2010. This material will be referred to as “10 Oz. Denim” in the report. Additional material tested: two commercial filter bags manufactured by Donalson Company, Inc. (Dura-Life and Tetratex (PTFE)), Kimberly-Clark Corp. Kleenguard A30 Breathable Coveralls, and a commercial cotton twill fabric obtained from JoAnn Fabrics.

SWATCH HOLDER MODEL

In order to mimic a swatch testing system used at RTI (RTI, International, Research Triangle Park, NC) that utilized a pressure drop across the swatch but no wind effect, see reference 3, a special fixture needed to be developed for wind tunnel use. The RTI apparatus was based on an ASTM Standard (F1215-89) for determining the filtering efficiency of flat-sheet filter media and subjects the swatch to a constant face velocity via a pressure drop across the material. The NAVAIR apparatus was designed to provide equivalent face velocities of the RTI tests of reference 3 while subjecting the swatch material to an external wind velocity. A tube with a sealed end allowed for a vacuum to be accurately and repeatably applied to the swatch and create a repeatable face velocity regardless of freestream wind velocity, see Figures A-9 and A-12. The length of the tube was designed to mitigate the effect of the bluff body shedding on the rear of the holder on the fabric penetration. In order to match the required flow rate vacuum pumps or makeup air were added as needed. The amount depended on the flow conditions, material tested, and the instrumentation used (e.g., the Aerodynamic Particle Sizer drew 5 liters/min and required makeup air for low wind tunnel speeds, see Figure A-10). A schematic of the swatch holder is shown in Figure A-13. The face velocity, U_O, is defined as:

$$U_O = \frac{Q}{A} \quad \text{(cm/sec)} \tag{1}$$

Where Q is the volumetric flow rate through the swatch and A is the cross-sectional area of the swatch exposed to the airstream (reference 4).

The swatch holder incorporated a 0.32 cm (1/8 in.) sampling tube located 2.54 cm (1 in. downstream of the swatch (inside the holder). The inner diameter of the swatch holder was 9.53 cm (3.75 in.). Note, the area of the fabric was 72.97 cm^2 (0.785 ft^2). A 15.24 cm (6 in.) diameter specimen was attached to the swatch holder via an automotive hose clamp. A 0.32 cm (1/8 in.) inner diameter sampling probe was also placed approximately 3.2 cm (1.25 in.) upstream (and in-line with the downstream probe) of the swatch, see Figure A-14.. Swatch permeability was determined at 1.27 cm (0.5 in.) of water pressure drop between a static pressure ring internal in the swatch holder and a static port on the upstream side of the swatch, reference 5.

<u>INSTRUMENTATION</u>

A TSI (TSI, Inc., St. Paul, MN) Model 3936 Scanning Mobility Particle Sizer (SMPS) was used to acquire particle count, size, and concentration data for sub-micron particles. This unit is composed of a TSI Model 3080 Electrostatic Classifier (with a long differential mobility analyzer (LDMA)) and a TSI Model 3025A Ultrafine Condensation Particle Counter. A 0.0457 cm impactor nozzle was used with an aerosol flow rate of 0.3 liters/min (lpm) and a sheath flow rate of 3.0 lpm to insure a 1-to-10 ratio as recommended by the manufacturer. Larger particles were measured using a TSI Model 3320 Aerodynamic Particle Sizer (APS). The various instrument settings are provided in Figure B-2.

The Syloid 244 (W.R. Grace, & Co., Lake Charles, LA) particle size was measured using a bench top nebulizer (Met One, Inc. Grants Pass, OR aerosol particle generator) and the APS. Aerosil and DOS particle size were measured using the SMPS.

To control the face velocity applied to the wind tunnel swatch, a Sierra Instruments, Inc. (Monterey, CA) Model C100M Mass Flow Controller was used to set the mass flow rate from a vacuum pump while a Sierra Instruments, Inc. Model 100-Series Smart-Trak Mass Flow Controller was used to control the flow bypass rate pulled from the sampling probes. The vacuum pump flow was controlled such that the total flow (SMPS flow, APS flow, makeup air, and sample probe bypass) provided the correct swatch face velocity as determined from a technique developed by NAVAIR and reported in reference 6.

Pressure differential between the four-port, static pressure array located on the inner wall of the swatch model fixture 2.54 cm (1 in.) downstream of the swatch and the pressure probe located on the upstream side of the swatch was measured using a digital pressure gage (Mensor Corp. San Marcos, TX, Model 2101).

PROCEDURE AND DATA REDUCTION

The NATF tunnel was allowed to thermally stabilize for over ½ hr before data acquisition commenced. Temperature was constant for a given tunnel speed, generally, 25.6 ºC at 18.3 m/sec (78ºF at 60 ft/sec). Isolated measurements of tunnel relative humidity were found to be 35%. After tunnel stabilization, sequential scans of particle sampling were conducted. The sequential scans proceeded with the freestream sampling probe (upstream of the swatch) followed by the swatch holder sampling probe (downstream of the swatch). 120 sec of data were taken for each scan for five downstream/upstream pairs. SMPS resolution was acquired at 64 channels per decade. For analysis the data was resolved to 16 channels per decade. Simultaneously, the APS acquired summation-mode data. Particle penetration was determined by dividing the average downstream sample (in units of dN/d log Dp) by the average upstream sample (in units of dN/d log Dp, where N is the number of particles and Dp is the particle diameter size). The subsequent data were plotted as penetration[4] versus particle size (nm).

$$P = N_{out} / N_{in} \tag{2}$$

Where N_{out} is the number of particles downstream and N_{in} is the number of particles upstream.

Note: dN/d log Dp is the differential or normalized particle size distribution based on particle number and normalized to one decade of particle size. This normalized concentration format allows particle size distributions to be compared regardless of channel resolution. In this way the present data is comparable to data taken at other facilities and with other instrumentation.

Comparison of the initial upstream/downstream particle count measurement with the final upstream/downstream particle count measurements was used to determine the existence of fabric loading due to particle deposition. If the last upstream/downstream sequence was significantly different from the initial upstream/downstream sequence in particle count, this would be a sign of fabric loading and would lead to erroneous penetration values. No data reported in this paper was affected by detrimental fabric loading due to particle deposition.

It should be noted that numerous background particle measurements were acquired throughout the course of testing: the data were consistently below 10 counts for SMPS particle sizes (and in most cases much below this value) and negligible for measurements acquired by the APS at larger sizes. No long term change in these background levels was observed.

CLARKSON BENCH TOP TESTS

Bench top permeation tests were carried out in 2007 by personnel of the Mechanical Engineering Department at Clarkson University and reported in reference 7. A schematic of the experimental setup is shown in Figure A-15 and utilized a 47 mm filter holder. An image of the setup is shown in Figure A-16. The fabric material used in reference 7 was from the same lot as used in the NAVAIR bench top experiments tested in 2013 (discussed in the following paragraph).

NAVAIR BENCH TOP TESTS

Bench top swatch testing was conducted to tie-in to the Clarkson University results and to provide penetration characteristics of various materials for a range face velocities. A schematic of the experimental setup is shown in Figures A-17 and A-18 and image of the setup are shown in Figure A-19.

ERROR ANALYSIS

As mentioned previously, the empty tunnel velocity spatial uniformity is approximately 1%. At a given spatial location in the test section, the tunnel velocity varied by approximately 0.5%. Tunnel temperature variations were less than 0.2°F. Experimental uncertainty was determined in a method outlined in reference 8 (Barlow, Rae and Pope) and the measured velocity was estimated to be with in ±1.45%.

Assessing the repeatability of the entire system was determined by testing a statistically significant number of samples and analyzing the results. This will be discussed in the next section.

DATA REPEATABILITY

Because this is a new method of testing swatch components and forms the basis in the development of a predictive tool to define penetration performance of material, it was important to be able to compare results on the same materials for a swatch test that does not incorporate an external wind source (e.g., reference 3). Another concern was to determine the robustness of the test setup and methodology: under what conditions was the system not effective, how repeatable were the results, and were the results repeatable in other facilities.

In view of these concerns, a parallel program was undertaken at the Mechanical Engineering Department at Clarkson University. The intent was for NAVAIR and Clarkson personnel to interact but produce independent results. NAVAIR personnel designed the swatch holder and Clarkson University manufactured two systems to be used at the NATF and Clarkson University Aerosol wind tunnel. As mentioned previously, Clarkson University personnel designed the dissemination system and focused efforts on maintaining uniform dissemination across the face of the swatch. Sampling of the disseminated particles, however, differed slightly between laboratories. While the upstream sampling probes were of similar design and location, the downstream probes used in the two efforts were in different locations. Clarkson University utilized a downstream probe approximately 10.2 cm (4 in.) from the rear of the swatch holder. NAVAIR utilized a downstream probe situated 2.54 cm (1 in.) from the rear face of the swatch material. The NAVAIR approach was to sample particles in-line with and in close proximity to the upstream probe, somewhat mitigating flow non-uniformities across the swatch.

In February 2007, Clarkson University personnel brought their dissemination system and in-house built SMPS (using in-house software) to NAVAIR for testing. Instrumentation differences between the two systems were found to be negligible. Additionally, tests using two methods of downstream sampling – one using a five-port array mounted one foot from the rear of the holder and a downstream port mounted 2.54 cm (1 in.) from the rear face of the swatch – were conducted. The five-port array, shown in Figure A-20, was designed to determine if internal flow mixing (or non-mixing) would adversely effect the downstream measurement. Both sampling methods were found to give similar penetration results. Data repeatability results will be presented in the results section.

RESULTS

PARTICLE DENSITY

The Aerosil tagging process was found to increase particle bulk density while decreasing peak particle size (Table B-1). Figures A-21 and A-22 show Scanning Electron Microscope (SEM) images for untagged and tagged fumed silicates. As seen in these images, the tagged particles appear less "fluffier" and have a smaller diameter than the untagged particles. As noted previously, unless otherwise noted, all data acquired in the present report utilized untagged challenge. The untagged Aerosil was determined to be 20 times less dense than DOS.

MATERIAL DEPENDENT FACE AND AMBIENT VELOCITY CORRELATION

The bench top swatch testing system was used to determine the correlation between fabric pressure drop and face velocity for a variety of fabrics, reference 6. As shown in Figure A-23, a generally linear relationship was found for all materials tested.

A correlation between fabric face velocity and wind tunnel speed was determined knowing the stagnation pressure drop across a constrained sleeve, see Figure A-24. The curves exhibit an exponential increase in face velocity with increasing wind speed. A material sleeve specimen was manufactured and attached to a pressure-instrumented spool. As seen in Figure A-25, a large mesh screen prevented material deformation under wind load. More details of this testing and technique may be found in reference 6.

The data in Figure A-24 were used to set the correct wind tunnel swatch face velocity at a given wind tunnel speed.

PARTICLE PENETRATION

REPEATABILITY OF RESULTS

Typical downstream and upstream data are shown in Figure A-26a and b for a bench top test using DOS as the challenge. The data were found to be repeatable and devoid of filter loading effects that would cause a variation in the downstream data over time for wind tunnel and bench top swatch tests.

The long-term repeatability of the system and the swatch material was assessed during previous testing. A total of 29 upstream/downstream particle count measurement pairs, using 7 different wind tunnel swatch specimens (taken from the same garment) was tested at a freestream velocity of 18.3 m/sec with an Aerosil challenge. As shown in Figure A-27, the results were found to be acceptably repeatable. The standard deviation of the measurements from the average was calculated to be less than 10%. This uncertainty was found to hold for all the repeat cases with fewer points. As inferred in Figure A-27, in-run repeatability was based more on the quality and consistency of the dissemination.

Figure A-28 shows typical repeatability for a sleeve test in the wind tunnel with Aerosil and DOS challenge using the SMPS and APS. In general, DOS was easier to disseminate and caused less clogging than Aerosil which resulted in better repeatability.

COMPARISON OF NAVAIR AND CLARKSON SMPS INSTRUMENTATION

A comparison of the effects of differences in SMPS instrumentation used by NAVAIR and Clarkson University personnel for data taken at the same time and with the same material using untagged Aerosil and tagged Cabosil is shown in Figure A-29 a and b. It was observed that there was no significant difference between any of the various Clarkson University/NAVAIR data pairs.

TIE-IN TO CLARKSON BENCH TOP TESTS

As mentioned, Clarkson University personnel performed bench top swatch testing in 2007 using different instrumentation and software, mass flow controllers, and dissemination system. As a check on the robustness of the developed techniques and systems, bench top swatch tests using the same challenge and material were conducted in 2013. As shown in Figure A-30, excellent agreement was found between the two test results.

EFFECT OF INCREASING FACE VELOCITY ON PENETRATION FOR BENCH TOP SWATCH TESTS – AEROSIL CHALLENGE

Figure A-31 shows the effect of increasing face velocity on fabric penetration for a bench top swatch test using an Aerosil challenge. In the legend the equivalent wind tunnel velocity for this material is estimated from the curves of Figure A-24.

Increasing face velocity equated to increasing particle penetration through the fabric. Greatest penetration was near 200 nm for all face velocities tested. At the highest face velocity of 27 cm/sec, particle penetration was found to be a maximum of 57% at approximately 190 nm.

EFFECT OF INCREASING FACE VELOCITY ON PENETRATION FOR BENCH TOP SWATCH TESTS – DOS CHALLENGE

Figure A-32 shows the effect of increasing face velocity on fabric penetration for a bench top swatch test using a DOS challenge. Increasing face velocity equated to increasing particle penetration through the fabric. Greatest penetration was generally between 200 nm to 250 nm for the face velocities tested. At the highest face velocity of 27 cm/sec, particle penetration was found to be a maximum of approximately 70 %. This is greater than the maximum penetration seen for an Aerosil challenge. In addition, the shape of the penetration curves were found to be different depending on the challenge used.

EFFECT OF INCREASING VELOCITY ON PENETRATION FOR WIND TUNNEL SWATCH TESTS – DOS CHALLENGE

Figure A-33 shows the effect of increasing face velocity on fabric penetration for a wind tunnel swatch test using a DOS challenge. As discussed previously, the face velocity was adjusted using a vacuum pump to match the equivalent face velocity on the stagnation point of a sleeve specimen at the same ambient wind speed determined from Figure A-24. Increasing wind tunnel velocity equated to increasing particle penetration through the fabric. Greatest penetration was generally between 200 nm to 250 nm for the face velocities tested. At the highest wind tunnel velocity of 30.5 m/sec, particle penetration was found to be a maximum of approximately 70 %.

COMPARISON OF WIND TUNNEL AND BENCH TOP SWATCH RESULTS

As shown in Figures A-34 through A-37, the wind tunnel swatch test results are compared to the bench top swatch test results. The bench top penetration curves were obtained by determining the appropriate face velocity of the material at a given wind tunnel speed using Figure A-24. Using this face velocity and an Akima curve fit routine (reference 9), a bench top penetration curve was interpolated from the data in Figure A-32. Generally, there is very good agreement between the data sets. It is noted there are slight discrepancies for the larger particle sizes: the wind tunnel swatch experiences higher penetration than the bench top swatch. However, the maximum penetration and the size at which the maximum penetration occurs were nearly identical between the wind tunnel swatch and bench top swatch results.

EFFECT OF PARTICLE DENSITY ON PENETRATION

As noted previously, the results from bench top swatch testing with an Aerosil challenge were seen to have less penetration than the results from bench top swatch testing with a DOS challenge. Figure A-38 shows that, at the lowest face velocity, the results using Aerosil as a challenge has a maximum penetration 30 % less than the maximum penetration using DOS as a challenge. In addition, the size where the maximum penetration occurs is approximately 100 nm smaller. This trend of lower penetration using an Aerosil challenge continues with increasing face velocity, see Figures A-39 through A41. However, the divergence between the two results narrow somewhat: at the highest face velocity, the results using Aerosil as a challenge has a maximum penetration 10 % less than the maximum penetration using DOS as a challenge and the size where the maximum penetration occurs is approximately 50 nm smaller. Note: the density of the Aerosil challenge was too low to use the APS.

DISCUSSION

Increasing the wind tunnel velocity was found to increase penetration (Figure A-33) in a manner similar to increasing the face velocity for the bench top swatch test (Figure A-32). This may seem intuitive and it may be thought that as long as the face velocity is the same as the bench top results then the penetration results would be equivalent to the wind tunnel results (as long as the wind tunnel velocity was not grossly different from the estimated face/wind tunnel velocity combination). This was found, inadvertently, to not be the case.

During the course of wind tunnel swatch testing at 6.1 m/sec, the face velocity was set to a value that was equivalent for a wind tunnel speed of 3.0 m/sec. As seen in Figure A-42, the penetration of particles through the material with the erroneous, lower face velocity for a wind speed 6.1 m/sec did not match the penetration at same face velocity but at the lower 3.0 m/sec wind speed. Thus, the external freestream velocity is an important factor in matching the penetration performance.

As mentioned previously, the particle density measurements showed that the untagged Aerosil particles were found to be 20 times less dense than the DOS particles. This could result in erroneous measurement of size distribution of Aerosil particles relative to DOS aerosol, because of the problem of multiple-charging. In the SMPS, particles of a selected mobility are classified out at any selected voltage. If the particles are predominantly singly-charged, the classified particles will be largely monodisperse. Particles larger than ~ 300 nm can be highly charged and when the fraction of these large particles is significant then their contribution to the particle count data in the channels corresponding to smaller particle sizes can be important. The SMPS incorporates an impactor that is designed to eliminate large particles from entering the LDMA. The particle diameter cut size of the impactor is determined by the nozzle used and the flow rate. For the present tests, a 0.0457 cm nozzle was used with a flow rate of 0.3 lpm, resulting in an expected cut size of 677 nm, see reference 10. This impactor cut size is calculated assuming an aerosol density of 1.0 g/ml. With the much lower density of Aerosil particles (0.05 gm/cc for untagged Aerosil), the impactor is not very effective in removing large Aerosil particles from the sample flow. Thus, the presence of multiple-charged particles must be considered for accurate size distribution measurement of Aerosil particles and this is not possible with the multiple-charge correction algorithm in the SMPS software. In this study, we used a new fit-based multiple-charge correction algorithm of reference 11 to recalculate the size distributions of the Aerosil particles. The penetrations were then recalculated from the size distributions obtained with the new multiple-charge correction algorithm. Our re-analysis with the new algorithm suggested that the effect of multiple charging on the penetration measurements was minimal.

The ability to correlate bench top swatch testing and the new wind tunnel swatch fixture/technique, as seen in Figures A-34 to A-37, allows IPE components to be tested (i.e., fasteners, closures, and seams may be tested and potentially improved using a variation of the wind tunnel swatch testing fixture or a modified bench top apparatus).

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CONCLUSIONS

A methodology was developed to test swatch materials at elevated wind speeds in the NATF wind tunnel. The developed dissemination system was found to be temporally and spatially repeatable. The particle penetration was found to increase with increasing wind tunnel velocity if the appropriate equivalent face velocity was applied to the wind tunnel swatch. Bench top swatch test particle penetration agreed with wind tunnel swatch results. The results were found to be consistent and repeatable and correlated well with data results taken at another facility using different instrumentation and procedures. The density of the particle challenge was found to have an effect on particle penetration. Aerosil, with a density twenty times less than Dioctyl sebacate, was found to have particle penetration from 10% to 30% less than the Dioctyl sebacate particle penetration. The ability to correlate bench top swatch testing and the new wind tunnel swatch technique allows the systematic testing IPE components, such as fasteners, seams, and closures, for improved system performance.

RECOMMENDATIONS

It is important to understand the effect of a less dense particle on aerosol instrumentation. Further research is recommended.

The results from this test lay out a methodology to determine material properties of IPE fabric. This methodology can also be used to identify suitable fabrics. In addition, this technique could be used to evaluate seams, closures, and fasteners to understand limitations and develop improvements.

The present work led to the initial development of component, or simulated sleeve, testing. However, this work is still in its infancy and much work needs to be accomplished to understand the flow physics inside and outside the component, the dynamics of material flapping, the effect of closures and seams, and particle penetration and deposition.

Computational modeling should be developed in parallel with the experimental effort to aid in the design of new fielded systems. Full-system tests should be carried out to determine if the modeling and experimental predictions and the testing methodology developed are adequate.

New particles with discreet properties, such as size and fluorescent excitation frequency uniqueness will need to be developed to assist in deposition measurements. The overall goal should be both an improved testing methodology and improved design capability.

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APPENDIX A
FIGURES

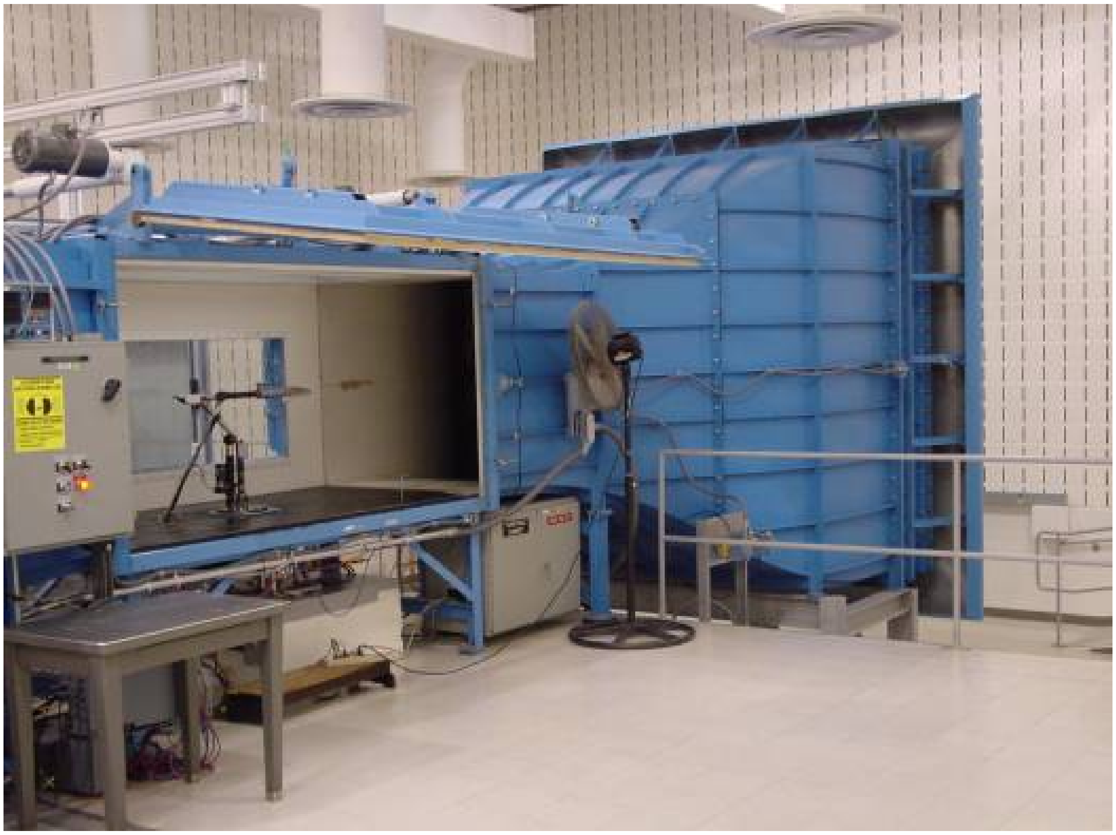


Figure A-1: NATF

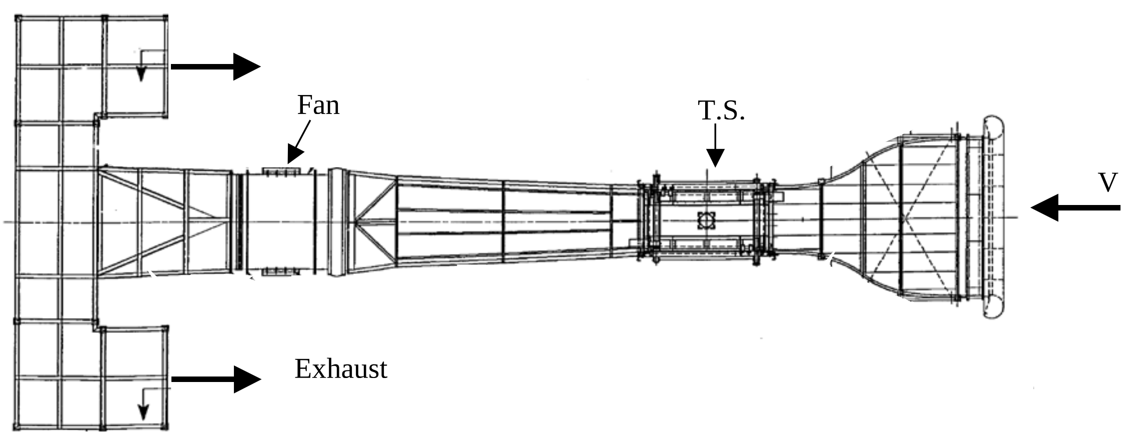


Figure A-2: Schematic of NATF

Figure A-3: Dispersion Box (Inset: with top removed)

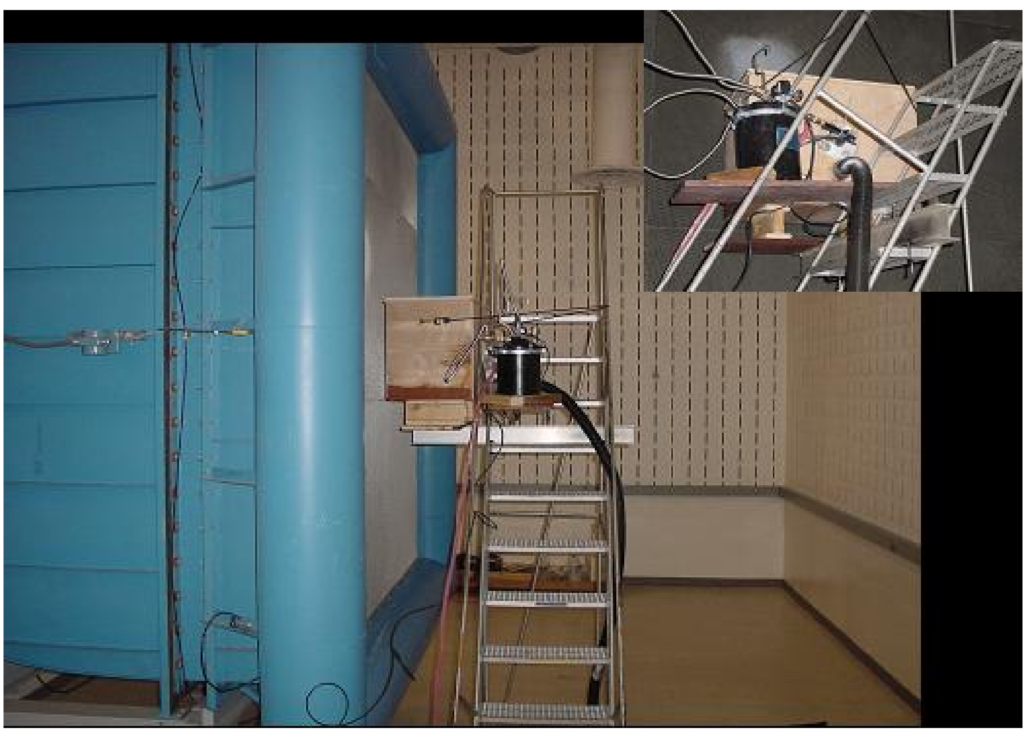


Figure A-4: Dispersion System Mounted in NATF (Inset: rear of system)

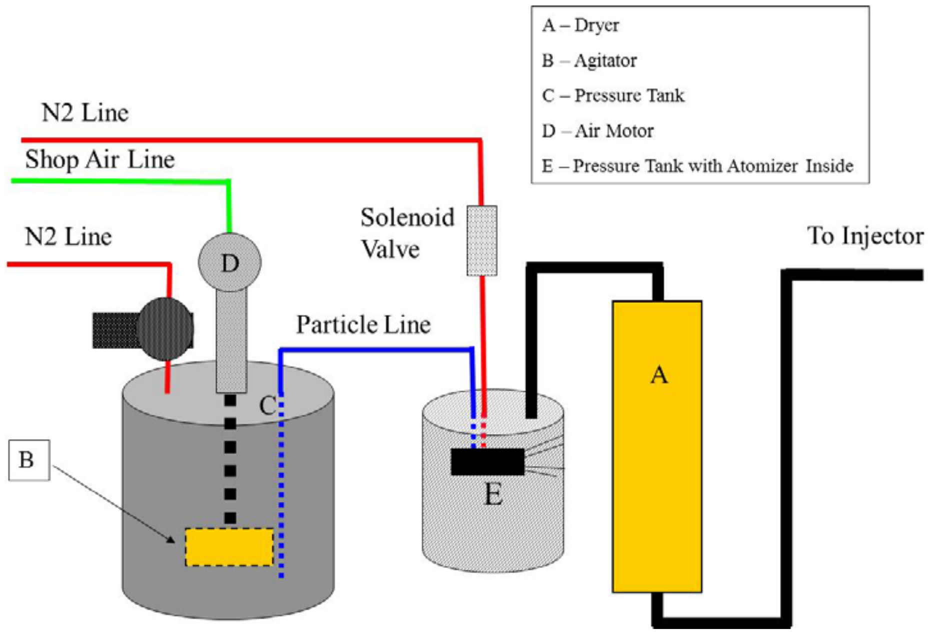


Figure A-5: Schematic of Aerosil Dissemination System - Wind Tunnel Swatch Testing

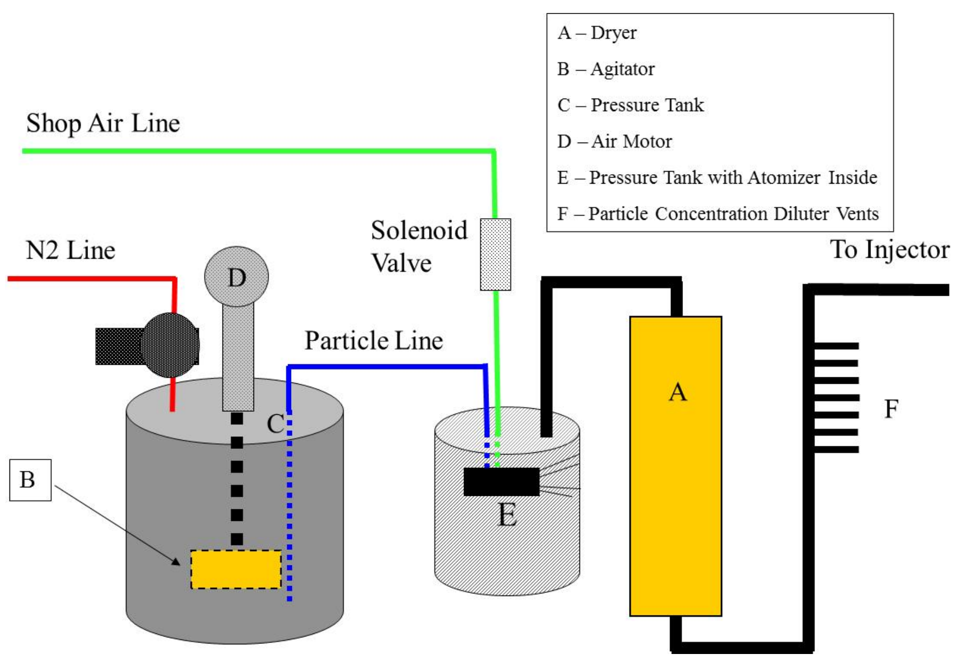


Figure A-6: Schematic of DOS Dissemination System - Wind Tunnel Swatch Testing

Figure A-7: DOS Dissemination System – Wind Tunnel Swatch Testing

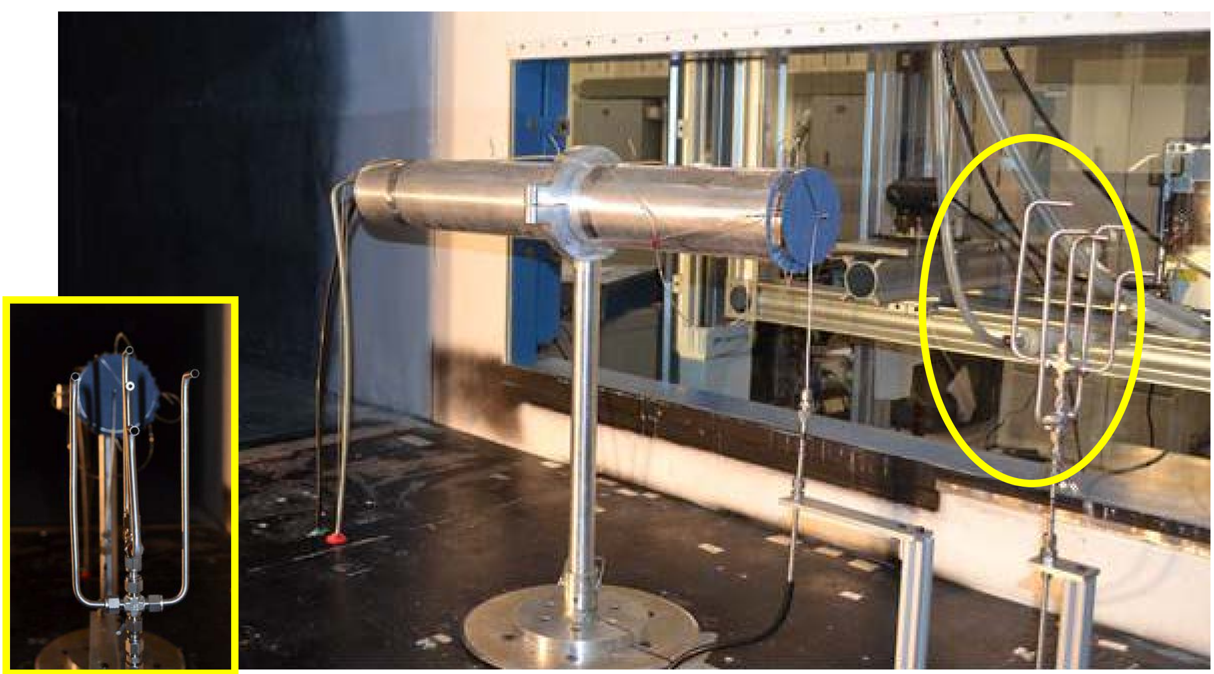


Figure A-8: Wind Tunnel Ejectors (Inset: Front View)

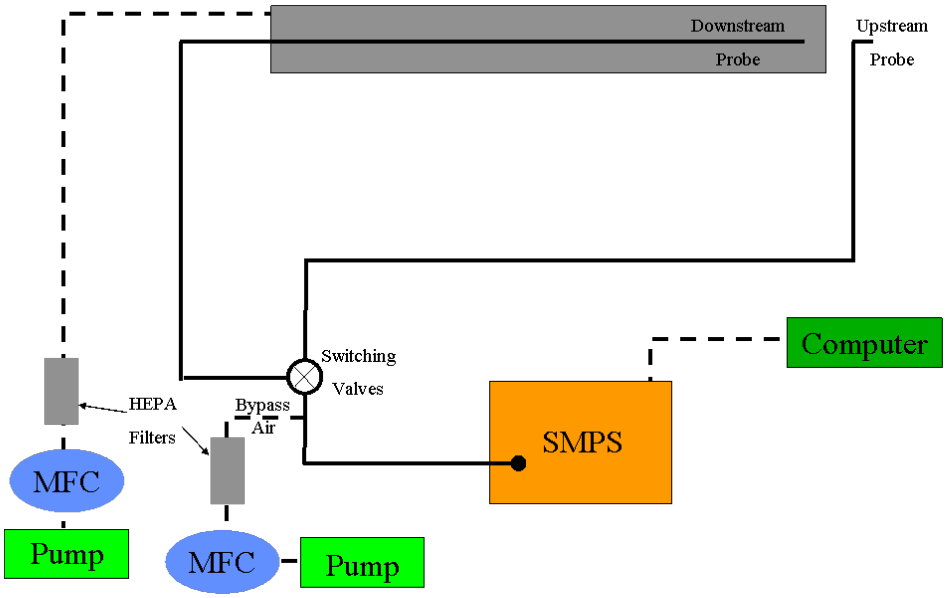


Figure A-9: Schematic of Wind Tunnel Swatch Holder Aerosil Challenge

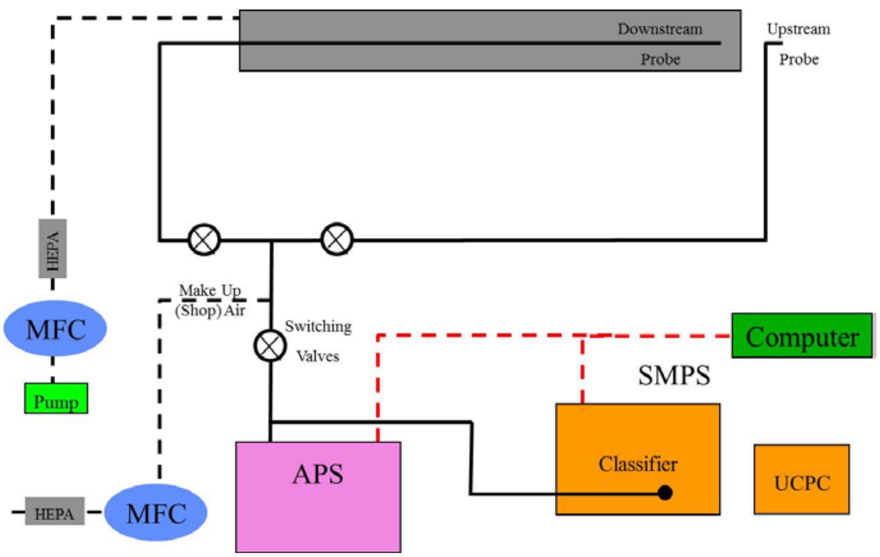


Figure A-10: Schematic of Wind Tunnel Swatch Holder DOS Challenge, Low Wind Tunnel Speed

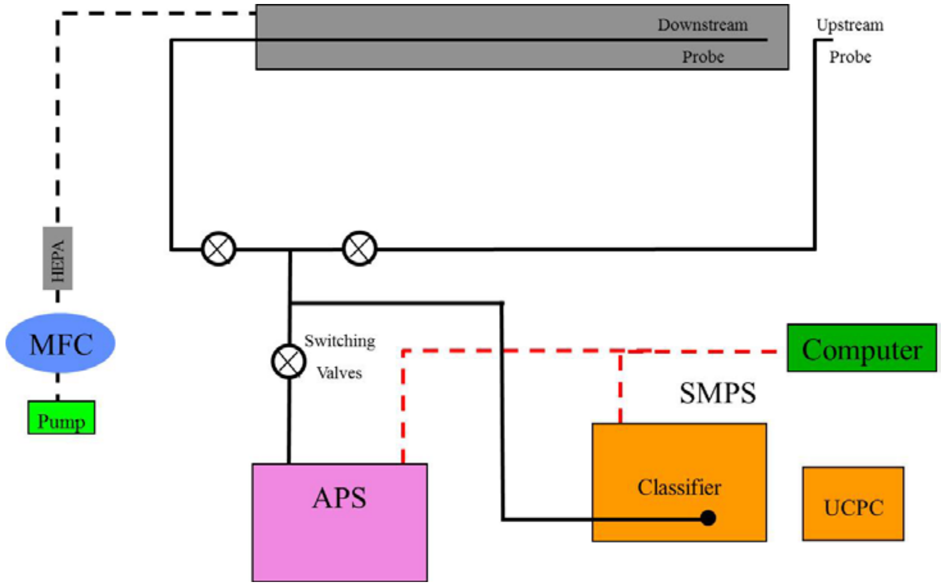


Figure A-11: Schematic of Wind Tunnel Swatch Holder DOS Challenge,
High Wind Tunnel Speed

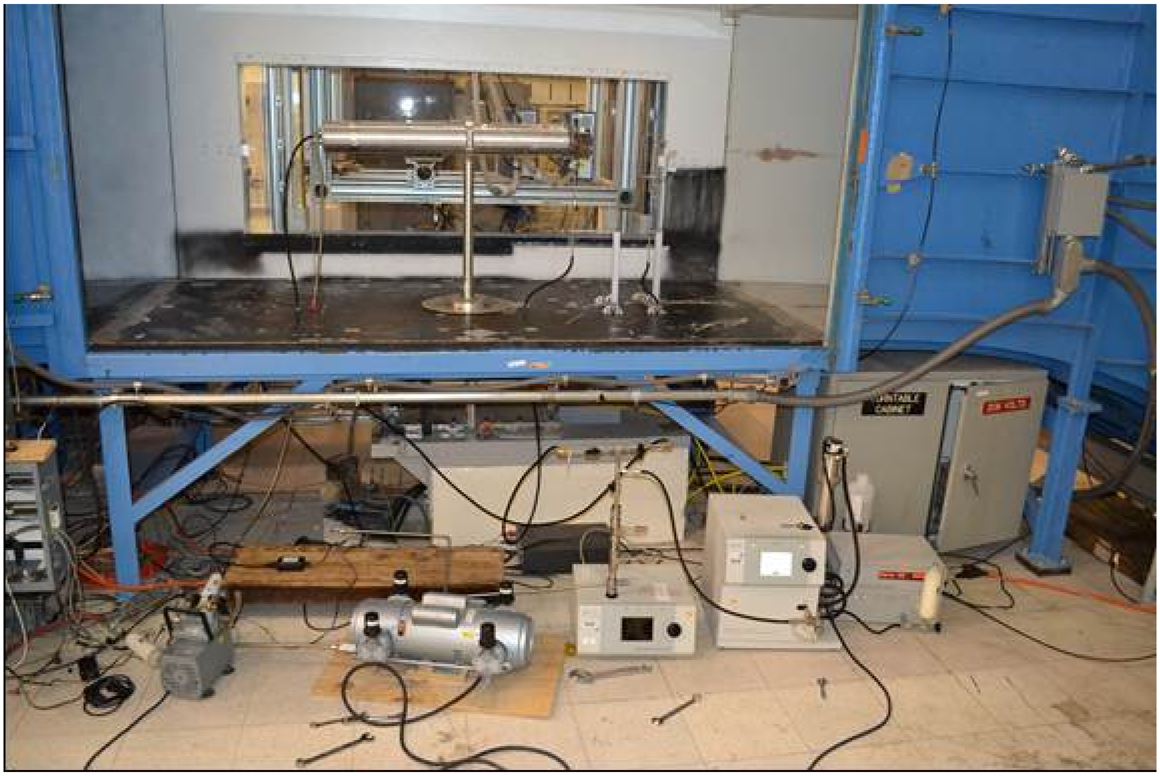


Figure A-12: Test Setup for Wind Tunnel Swatch Testing

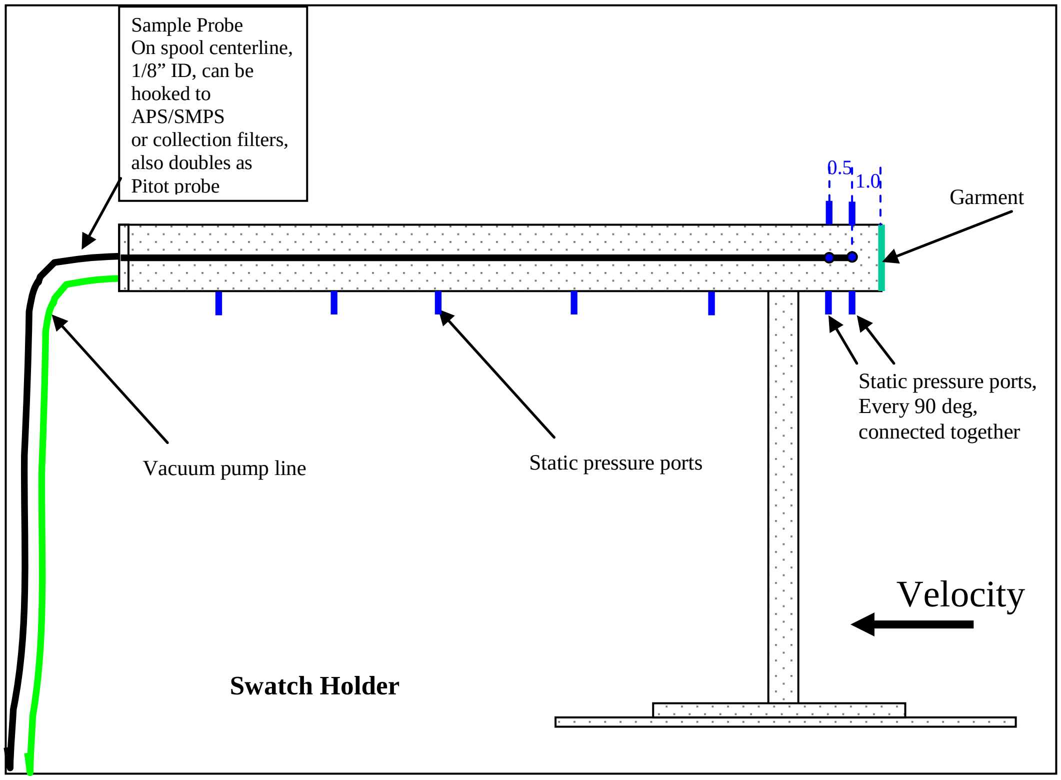


Figure A-13: Schematic of the Swatch Holder in the NATF Wind Tunnel

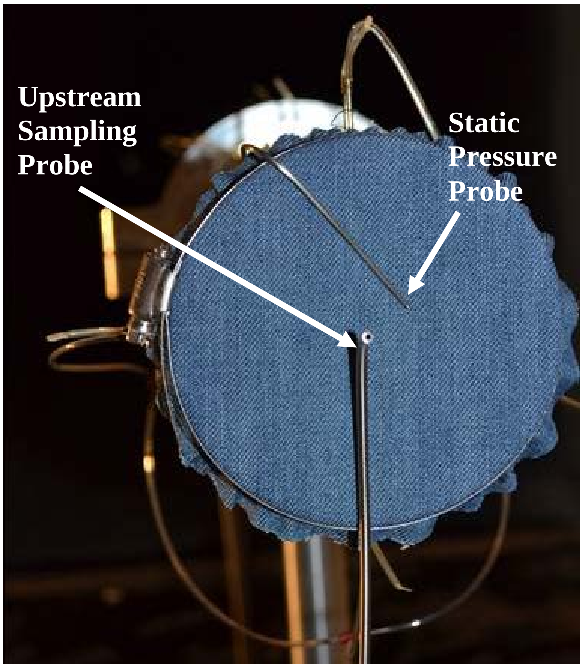


Figure A-14: Front of Wind Tunnel Swatch Holder with Upstream Sampling Probe and Static Pressure Probe

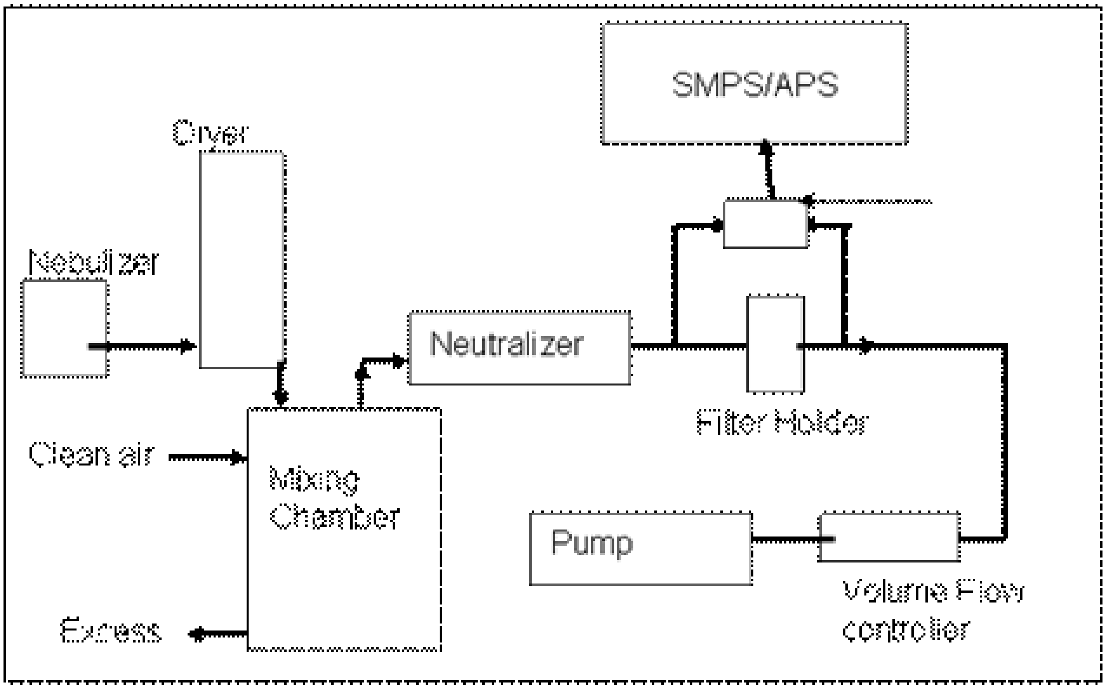


Figure A-15: Schematic of Bench Top Setup at Clarkson University, reference 7

Figure A-16: Clarkson Bench Top Filter Test Setup

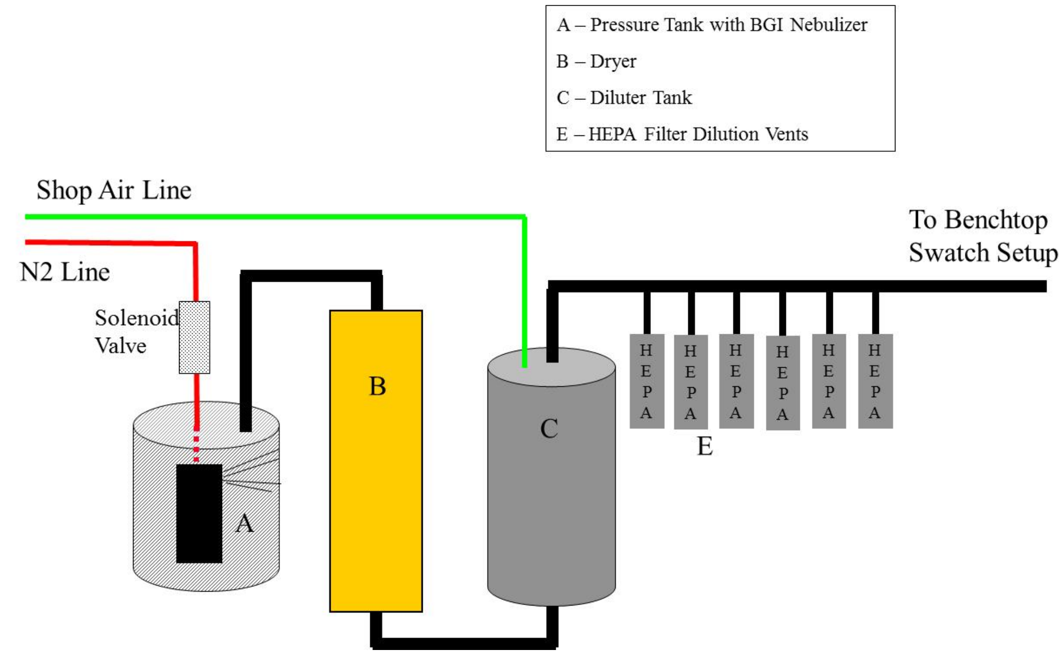


Figure A-17: Schematic of NAVAIR Bench Top Dissemination System

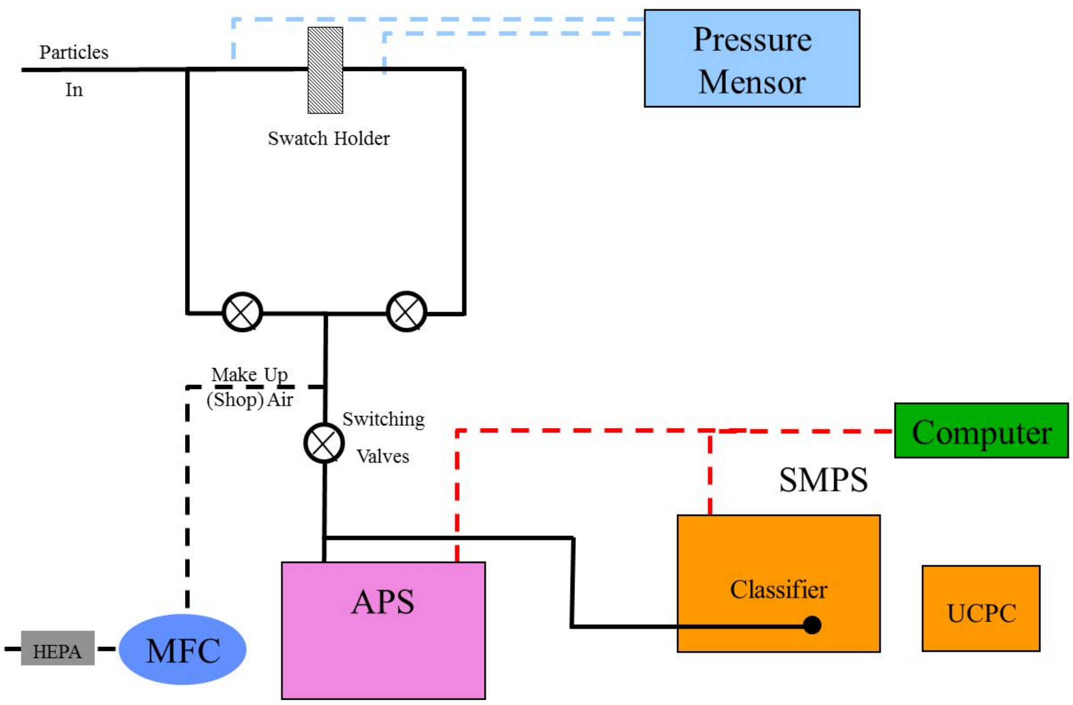


Figure A-18: Schematic of NAVAIR Bench Top Testing System

Figure A-19: NAVAIR Bench Top Testing System (DOS Challenge)

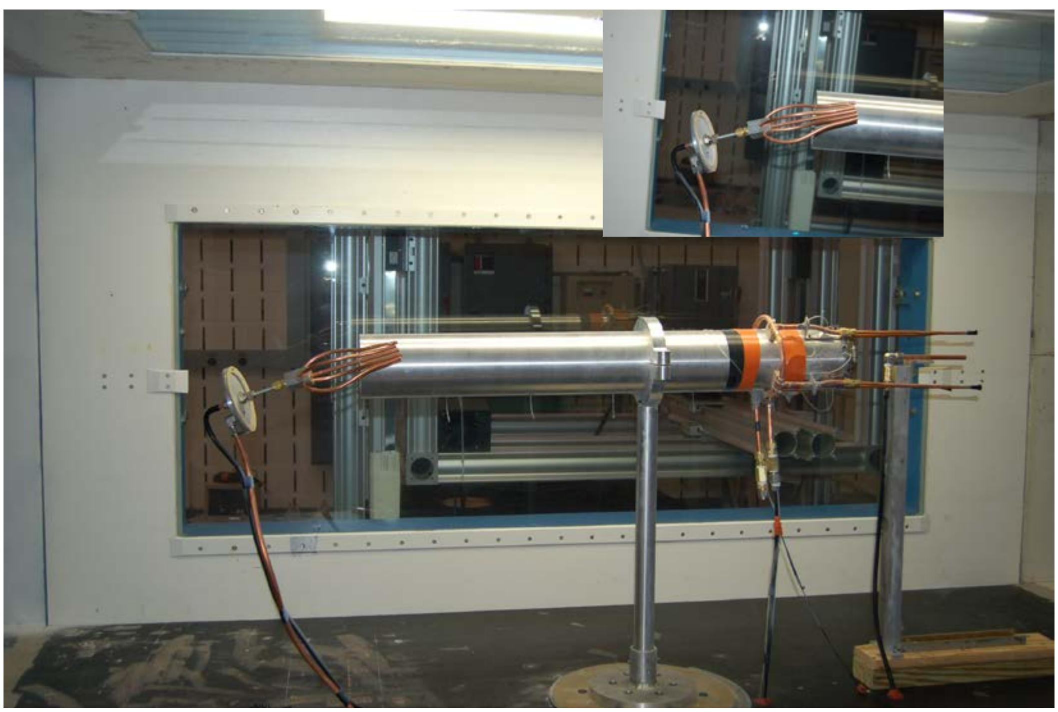


Figure A-20: Original Five-Port Sampling Probe (Inset is Enlarged View)

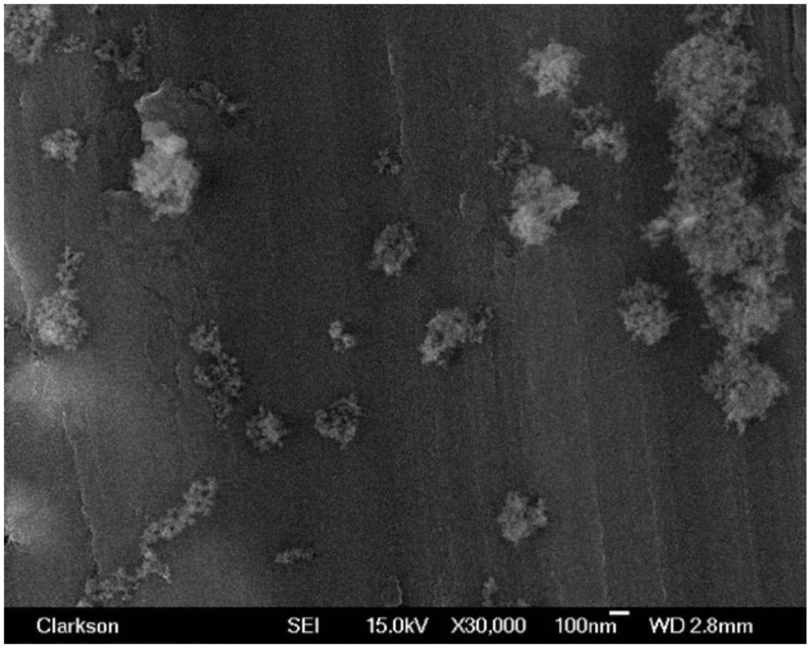


Figure A-21: Untagged Fumed Silicate Image Using SEM (Courtesy of Clarkson University)

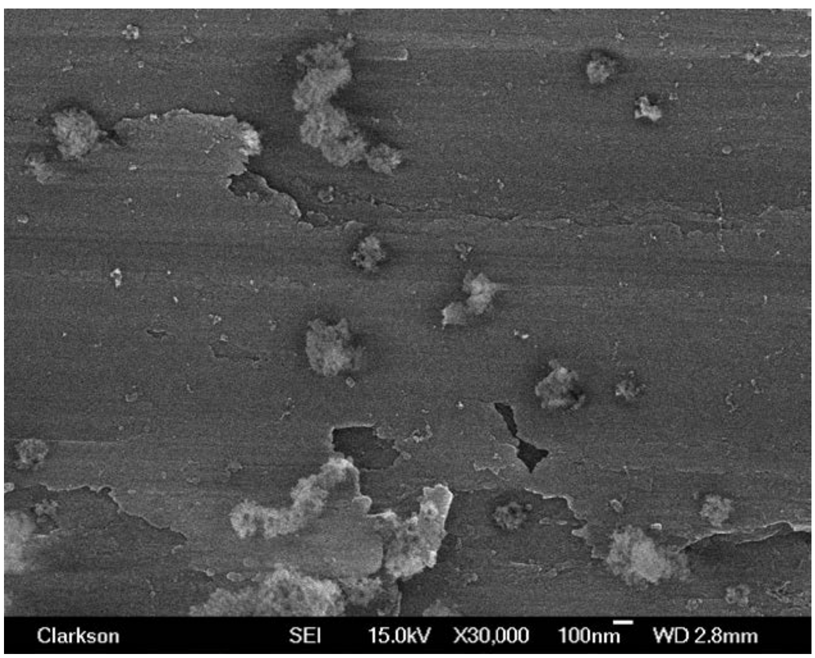


Figure A-22: Tagged Fumed Silicate Image Using SEM (Courtesy of Clarkson University)

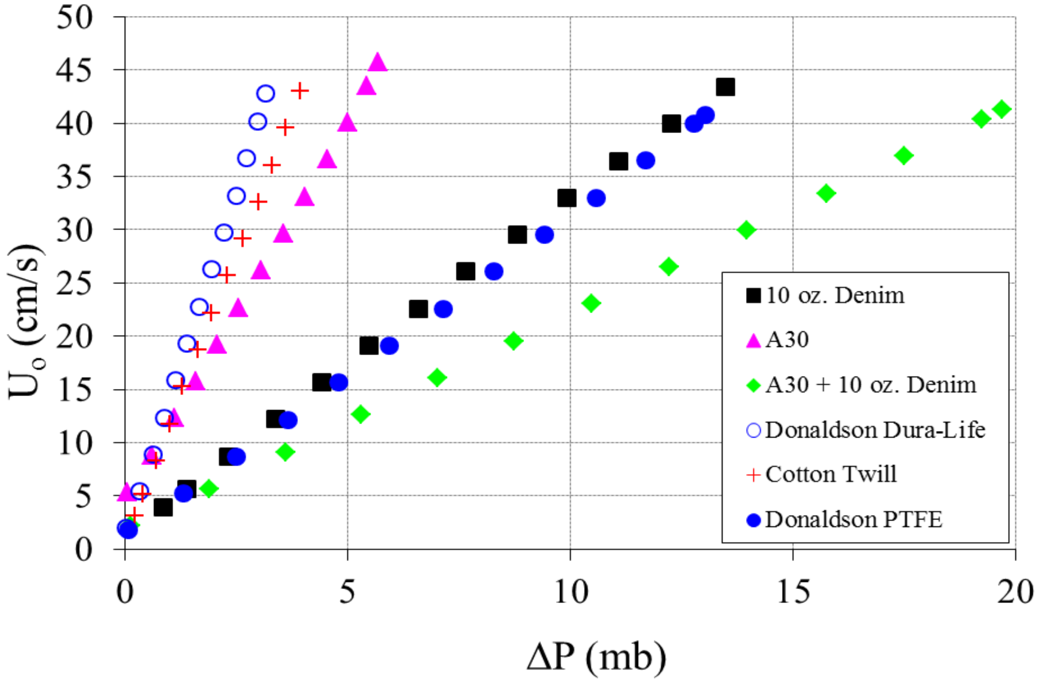


Figure A-23: Face Velocity Variation with Pressure Drop for Various Materials

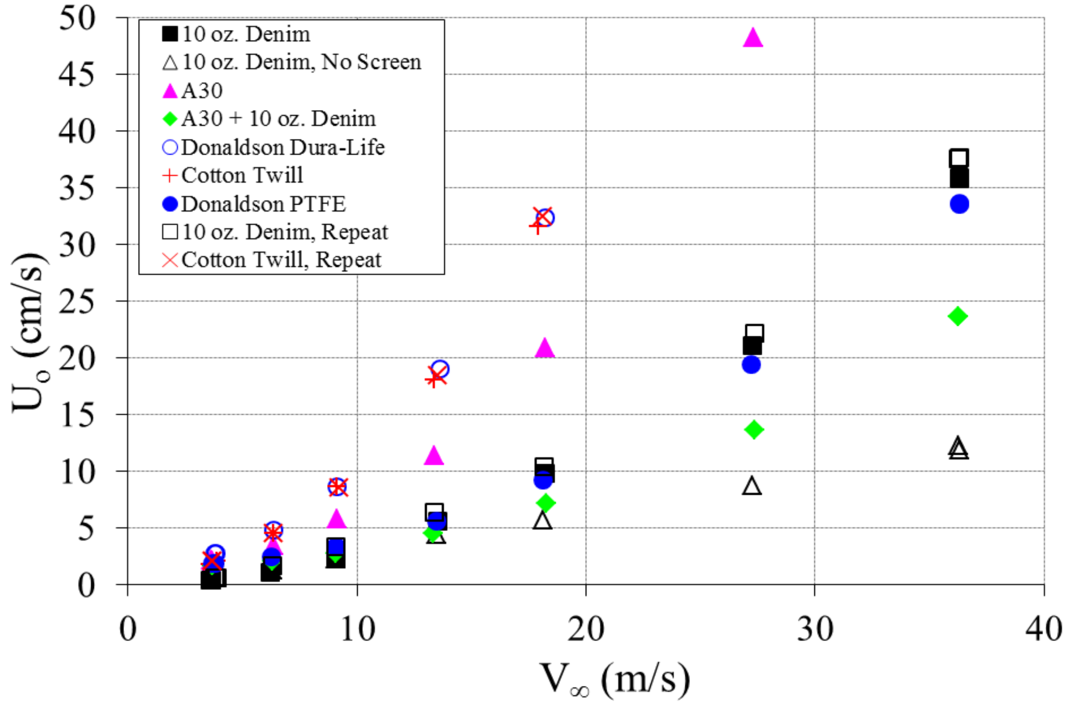
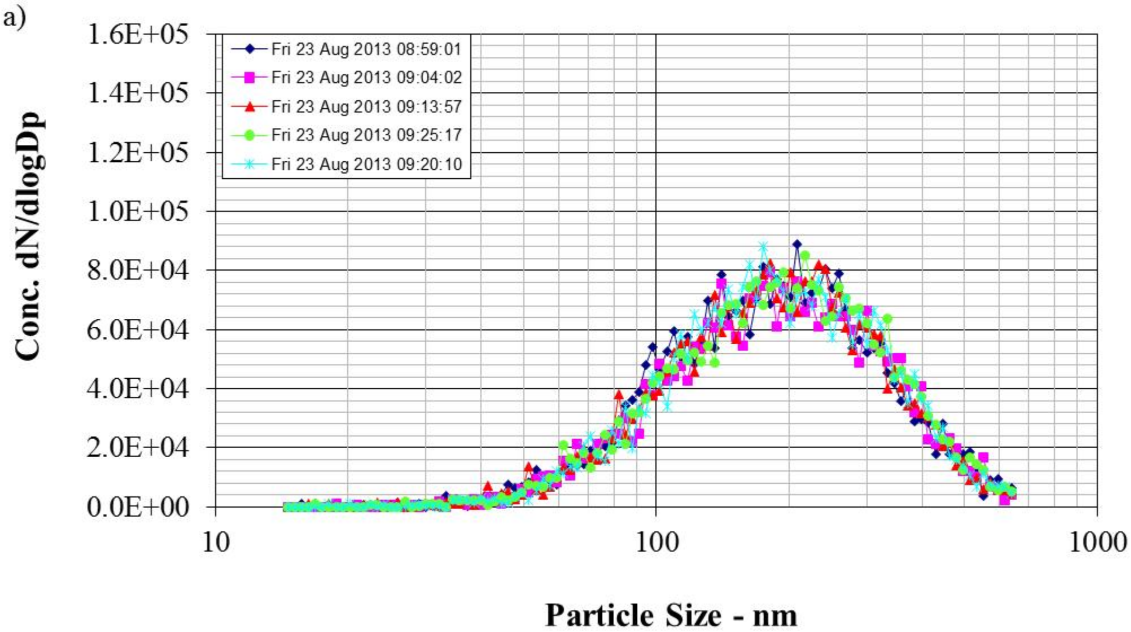


Figure A-24: Face Velocity Variation with Wind Tunnel Speed Determined from Wind Tunnel Sleeve Testing

Figure A-25: Sleeve Component Fixture: a) Support Screen, b) with Installed Sleeve over the Support Screen, and c) with Installed Sleeve without Support Screen a)



b)

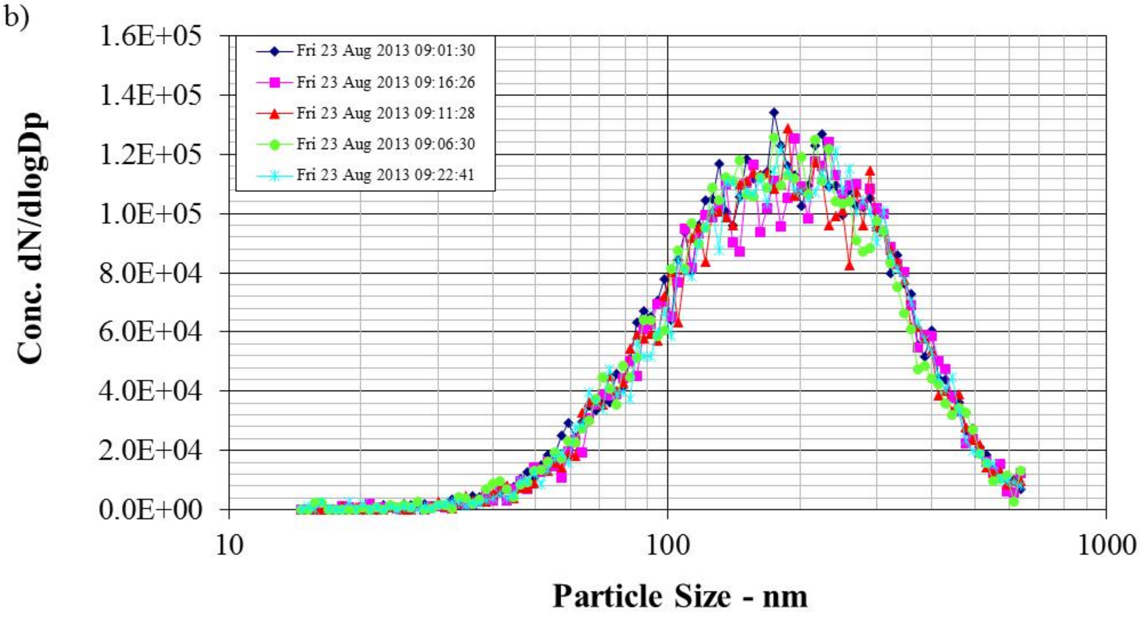


Figure A-26: Typical In-Test Repeatability, Bench Top, DOS Challenge: a) Downstream Sample and b) Upstream Sample

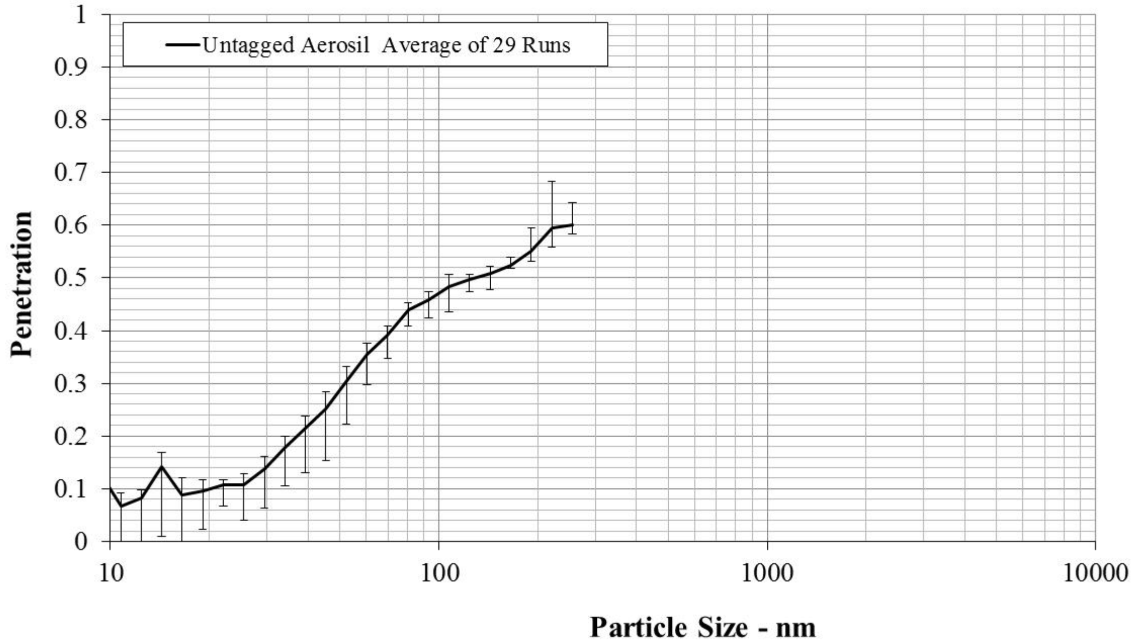


Figure A-27: System Repeatability, Aerosil Challenge, Wind Tunnel Swatch Testing, 18.3 m/sec

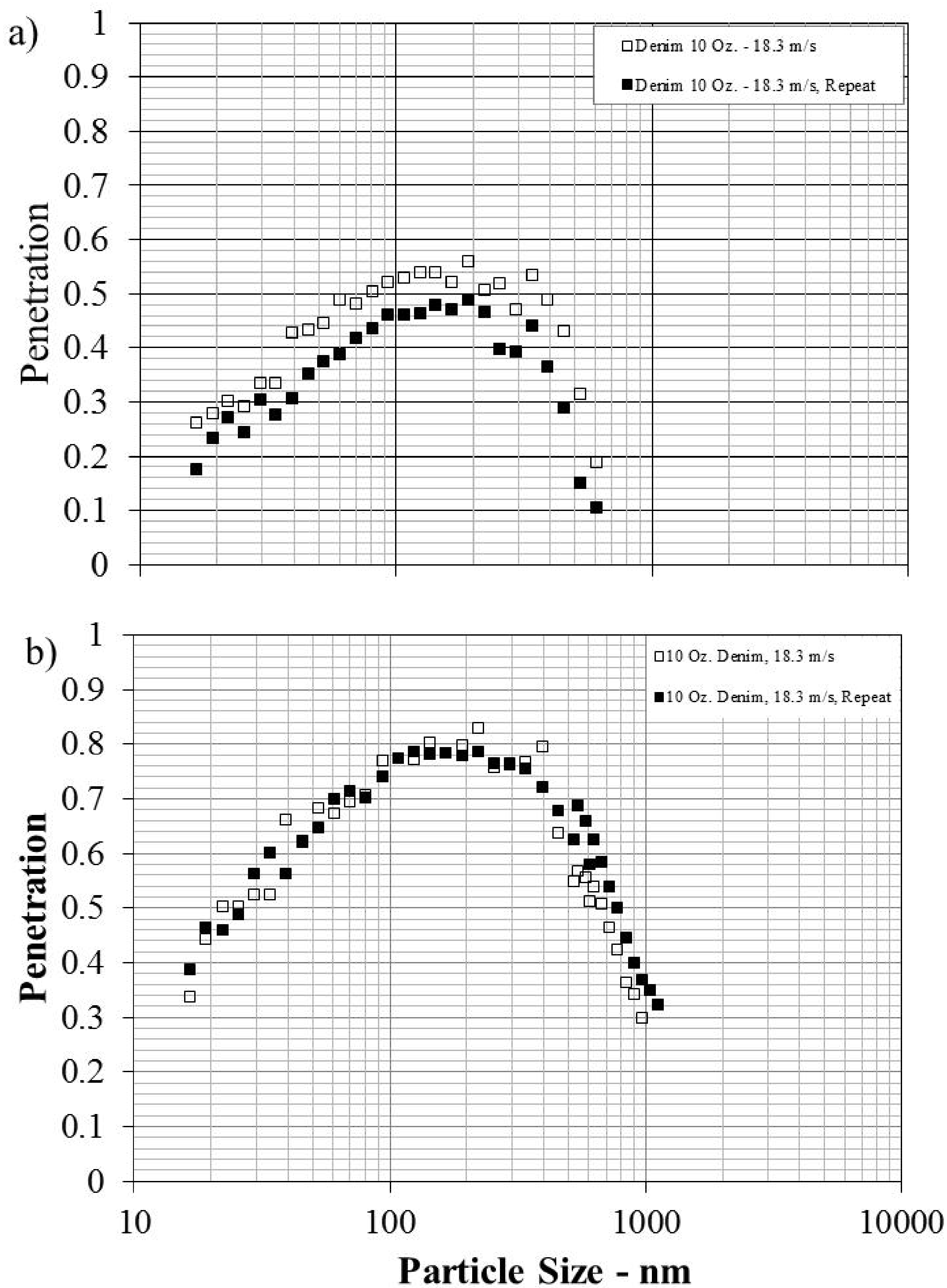


Figure A-28: System Repeatability, Wind Tunnel Sleeve Testing, 18.3 m/sec: a) Aerosil Challenge and b) DOS Challenge

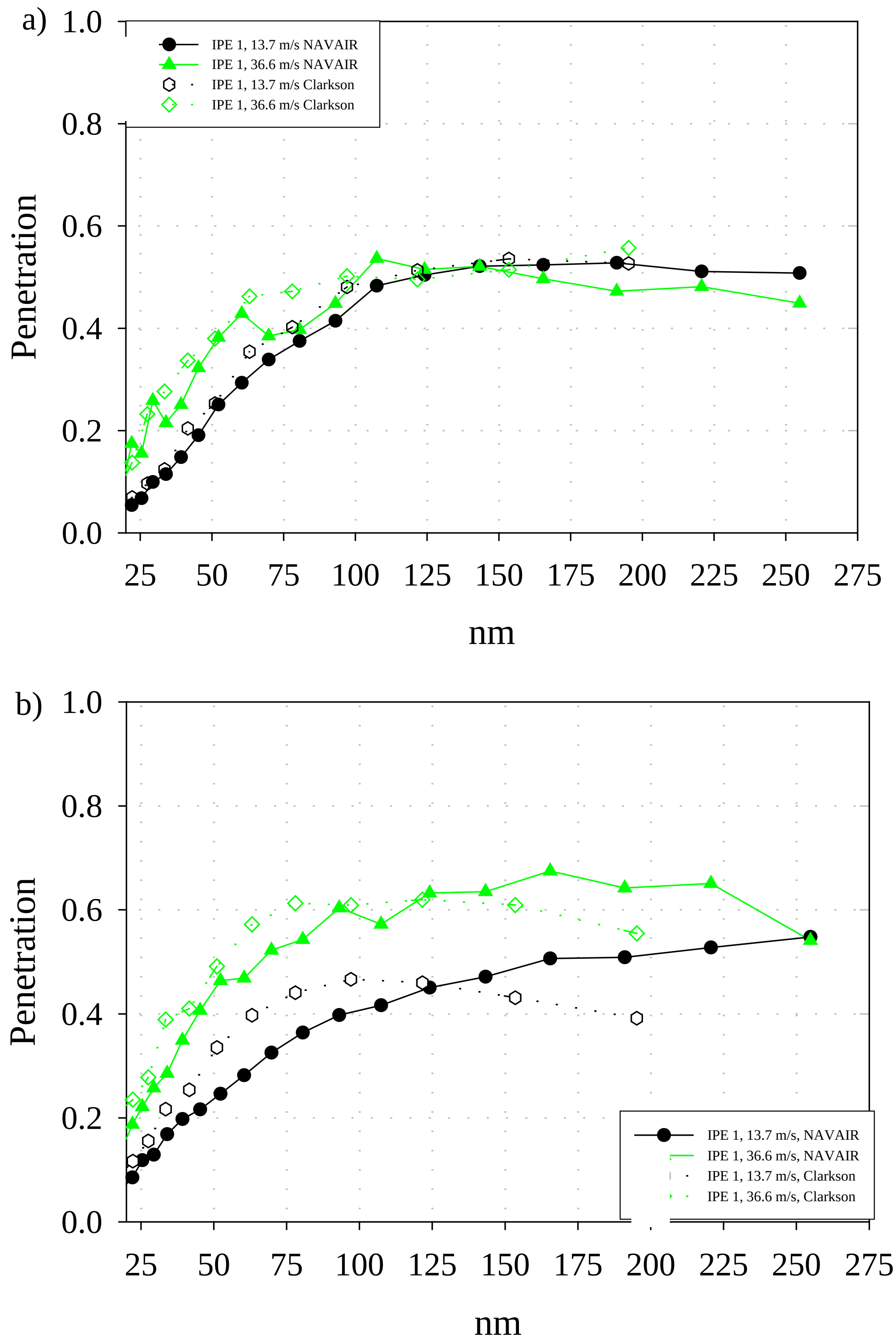


Figure A-29: Comparison of Clarkson and NAVAIR SMPS Instruments Wind Tunnel Swatch Test with a) Untagged Aerosil and b) Tagged Cabosil Challenges

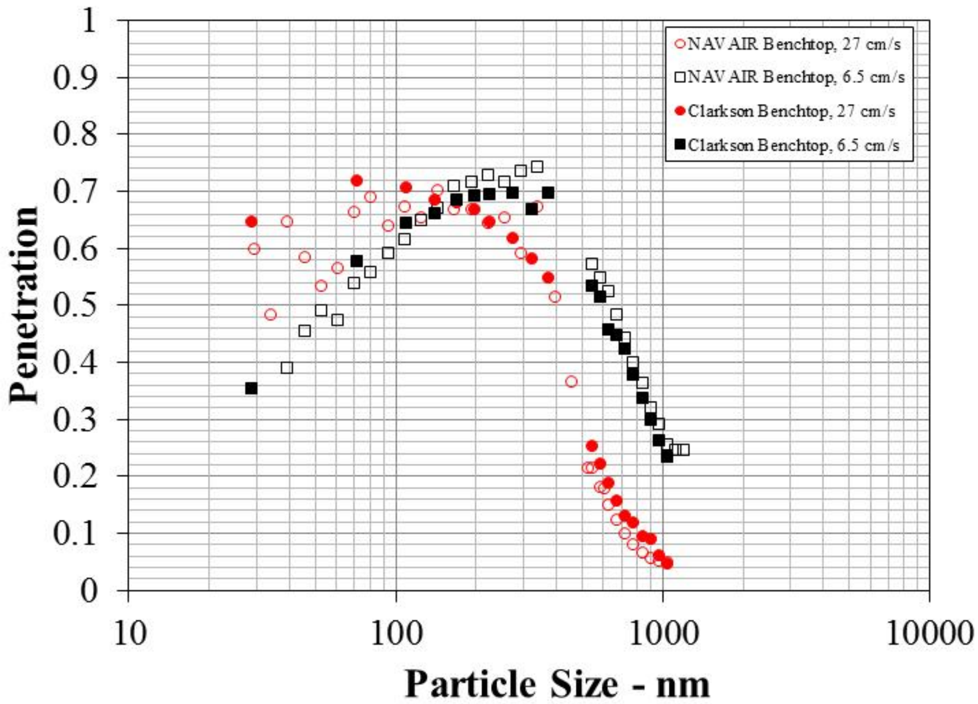


Figure A-30: Comparison of Clarkson and NAVAIR Bench Top Swatch Test Systems (Clarkson Data from reference 7)

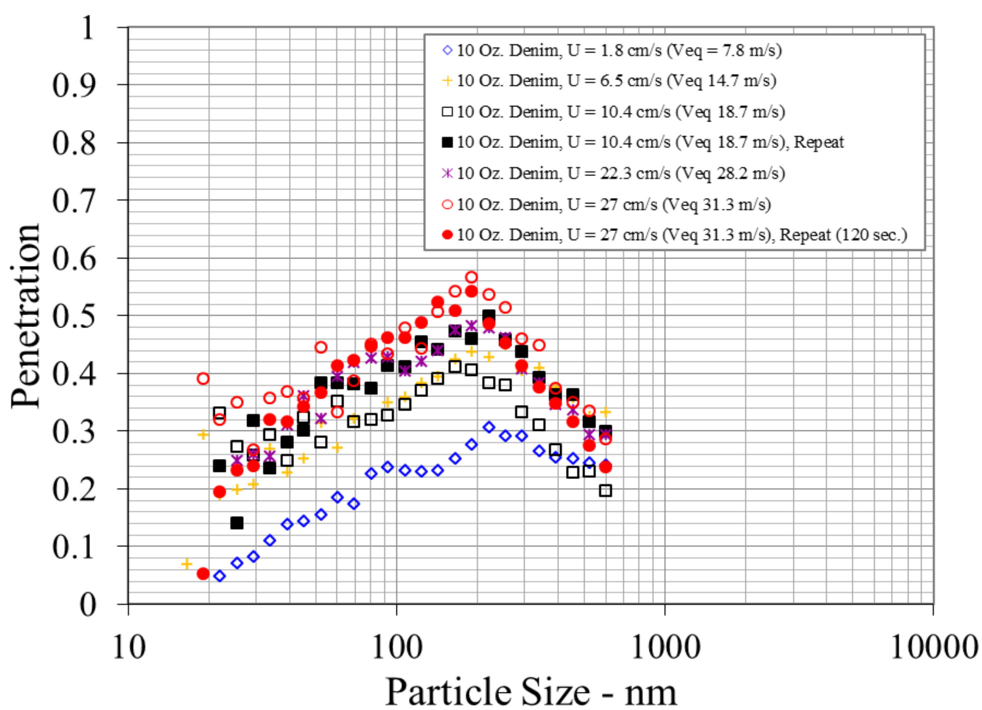


Figure A-31: Bench Top Swatch Test, Increasing Face Velocity, Aerosil Challenge

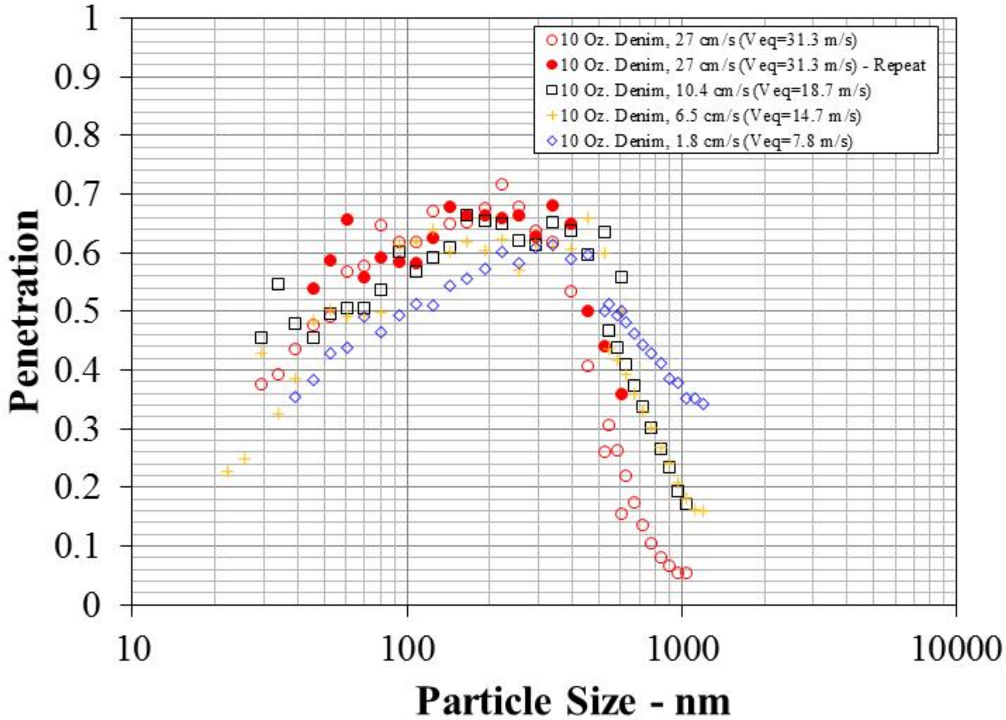


Figure A-32: Bench Top Swatch Test, Increasing Face Velocity, DOS Challenge

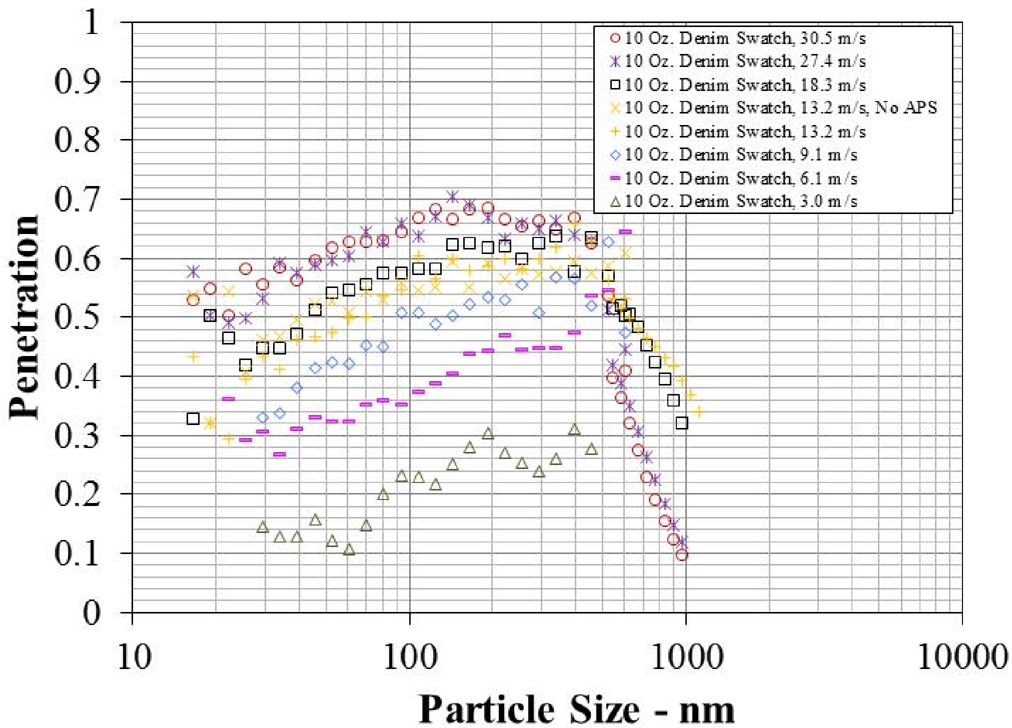


Figure A-33: Wind Tunnel Swatch Test, Increasing Face Velocity, DOS Challenge

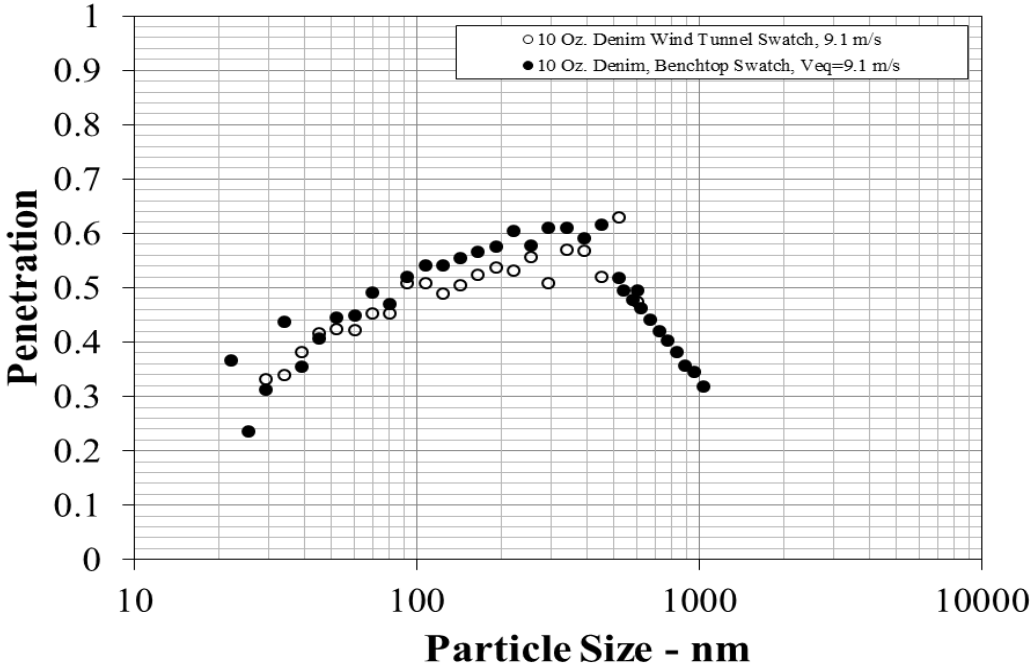


Figure A-34: Comparison of Wind Tunnel and Bench Top Swatch Results, DOS Challenge, V_{∞}=9.1 m/sec

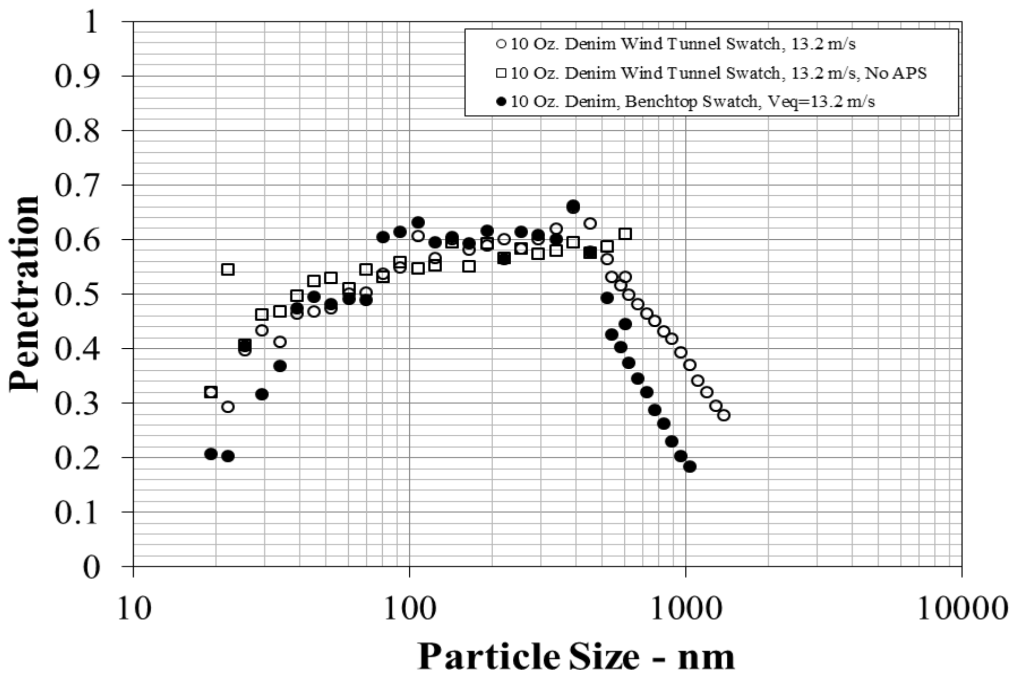


Figure A-35: Comparison of Wind Tunnel and Bench Top Swatch Results, DOS Challenge, V_{∞}=13.2 m/sec

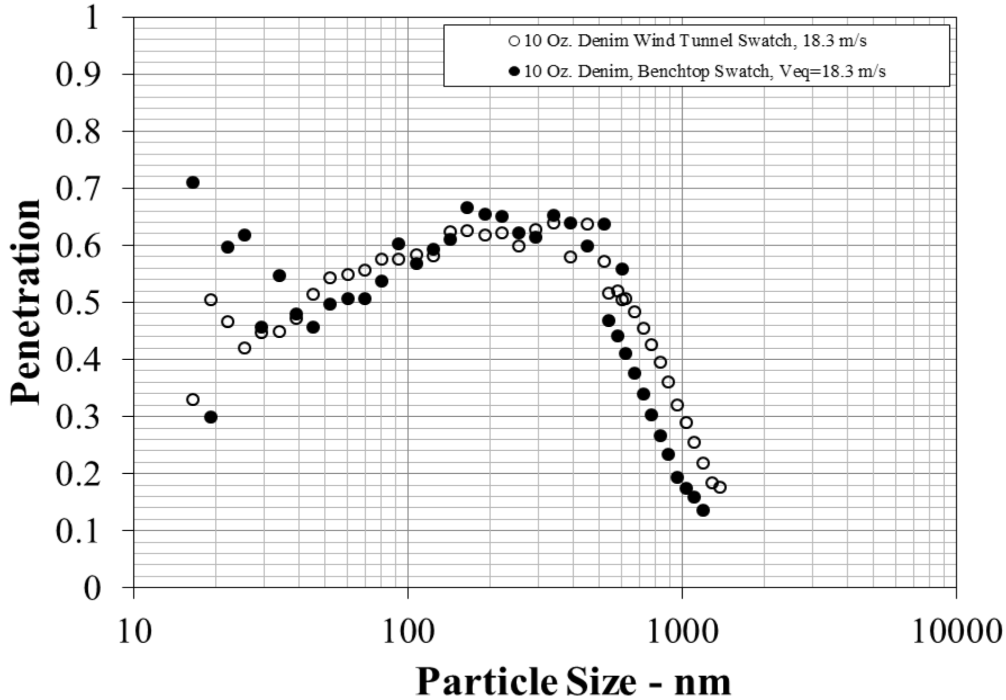


Figure A-36: Comparison of Wind Tunnel and Bench Top Swatch Results, DOS Challenge, V_∞=18.3 m/sec

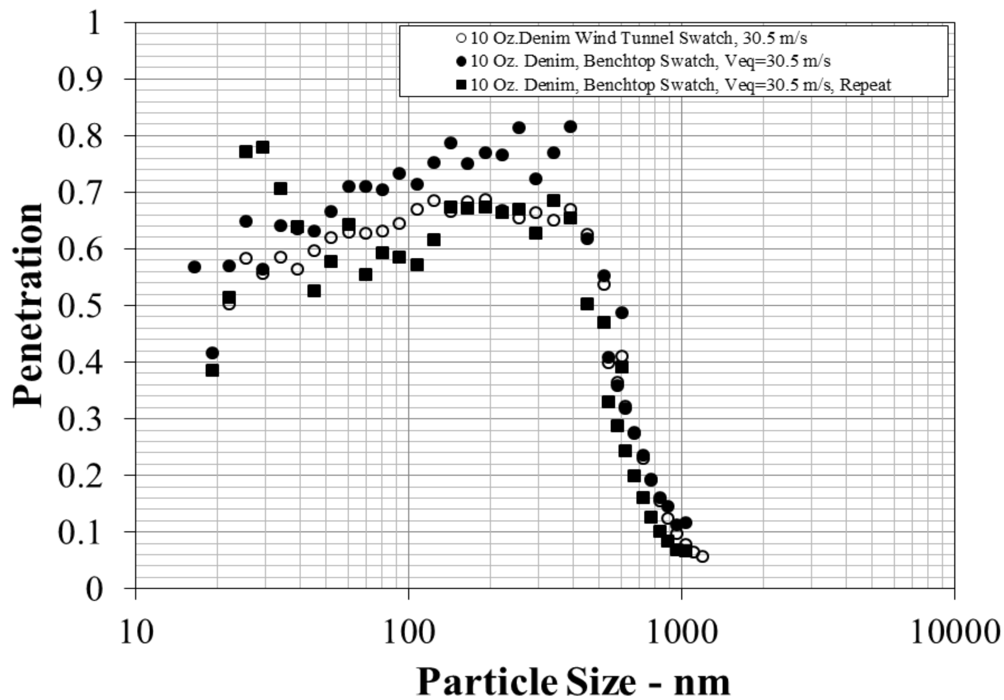


Figure A-37: Comparison of Wind Tunnel and Bench Top Swatch Results, DOS Challenge, V_∞=30.5 m/sec

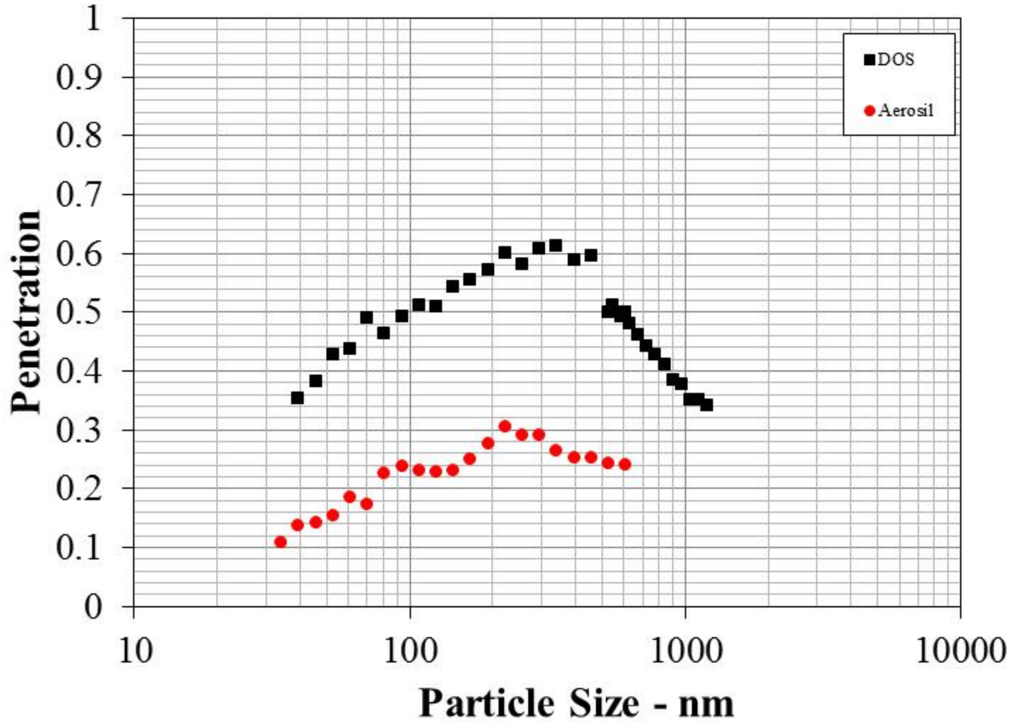


Figure A-38: Effect of Challenge on Bench Top Swatch Penetration, U_o=1.8 cm/sec

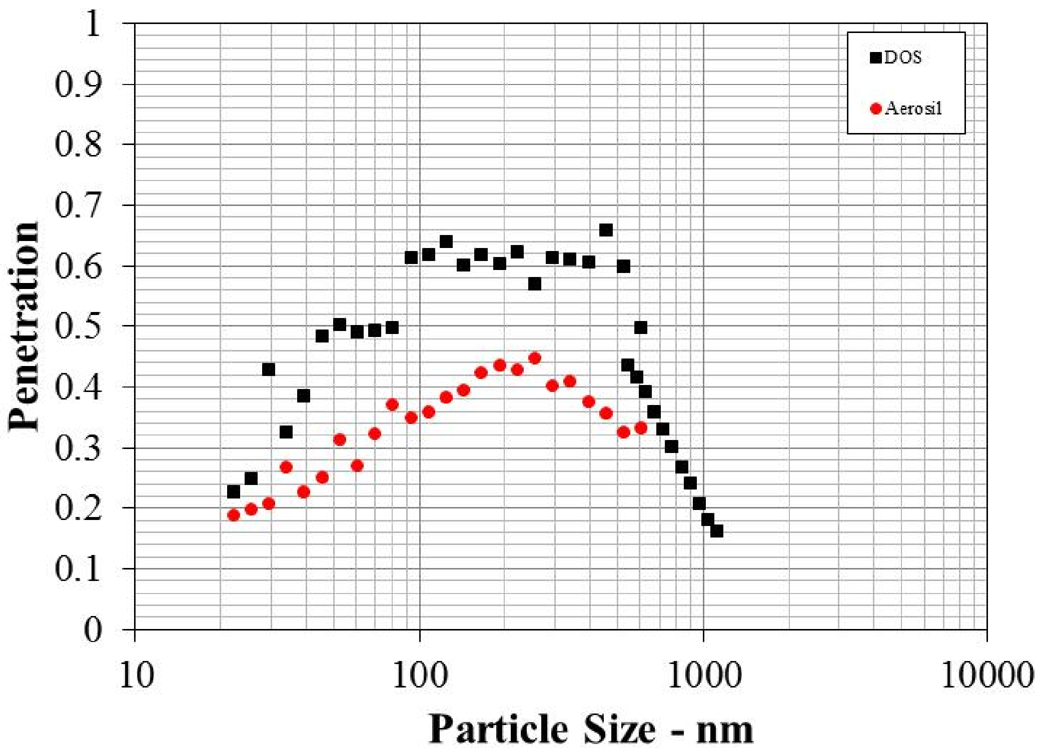


Figure A-39: Effect of Challenge on Bench Top Swatch Penetration, U_o=6.5 cm/sec

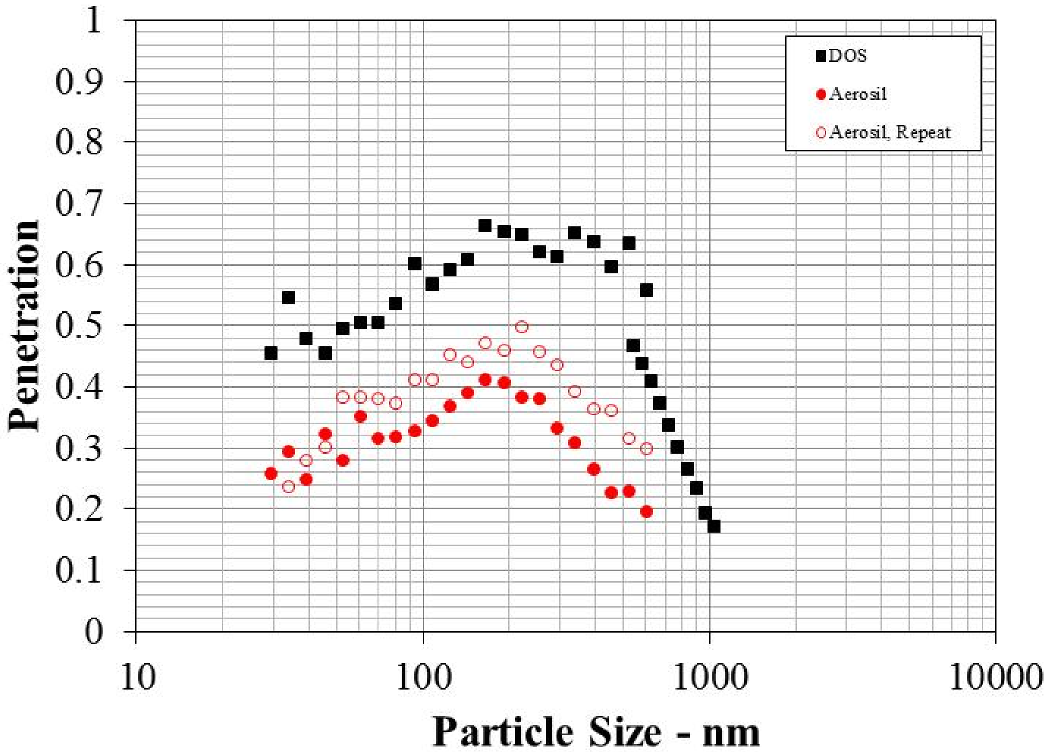


Figure A-40: Effect of Challenge on Bench Top Swatch Penetration, U_o=10.4 cm/sec

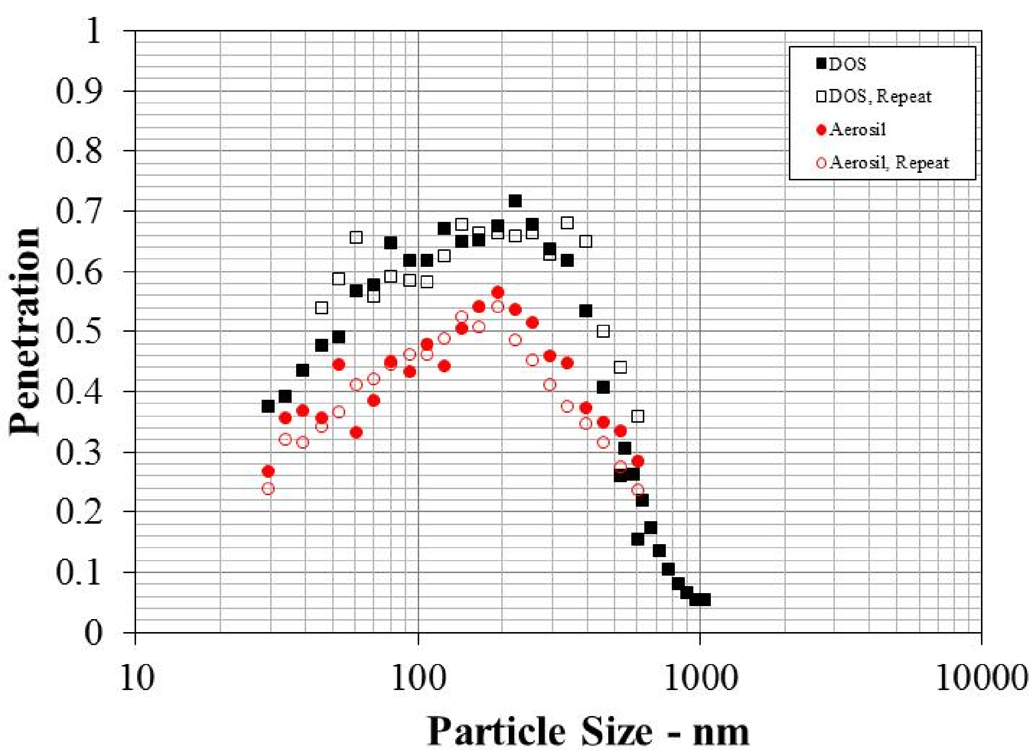


Figure A-41: Effect of Challenge on Bench Top Swatch Penetration, U_o=27 cm/sec

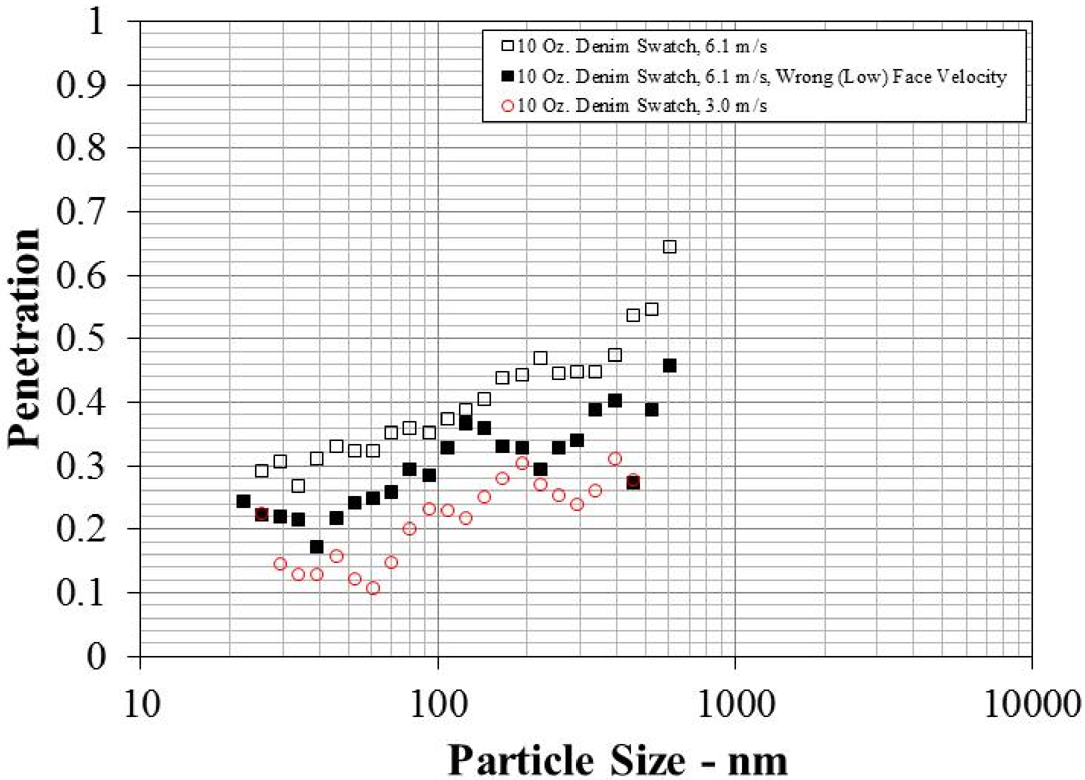


Figure A-42: Effect of Erroneous, Lower Face Velocity

APPENDIX B
TABLES

Table B-1: Bulk Particle Density and Size Estimates of Various Particles

Type	Density - g/ml	Std. Dev.	Peak Diameter (mean) - nm	Diameter Std. Dev. - nm
Aerosil 380 -Untagged	0.0450	0.0038	108	34
Aerosil 380 -Tagged	0.1082	0.0062	70	10
Cabosil -Untagged	0.0330	0.0021	109	22
Cabosil -Tagged v1	0.1041	0.0051	75	28
Cabosil -Tagged v2	0.1025	0.0030	NA	NA
Syloid 244 - Untagged	0.1226	0.0033	1040	NA
Glass Bead	0.9444	0.0456	NA	NA
Arizona Road Dustr	0.8072	0.1084	NA	NA
DOS	0.9140	NA	106	5

Table B-2: Instrumentation Settings

SMPS:	
Charge Correction	On
t_d (Delay Time)	3.3 s
Impactor	0.0457 cm
DMA	3081
CPC Model	3025A
CPC Flow	Low
Up scan	120 s
Down Scan	15 s
Sheath Flow	3 lpm
Aerosol Flow	0.3 lpm
Low Voltage	10 V
High Voltage	9630 V
Size Range	14.3 nm to 673 nm
t_f	7.4 s
D50	678 nm
APS:	
Dilution/Efficiency File	00100to1.e20
Particle Density (DOS)	0.914 g/cc
Stokes Correction	On
Channel	<0.523 to 20.535 micron
Sample Time	120 s
Summation	Channel and Raw data

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